An Astrobiology Strategy
for the Search for Life in the Universe

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AND MEDICINE

Committee on the Astrobiology Science Strategy for the Search for Life in the Universe

Space Studies Board

Division on Engineering and Physical Sciences

A Consensus Study Report of

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[1] FRSC, Fellow, Royal Society of Canada.
[2] NAS, Member, National Academy of Sciences.
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Preface

Astrobiology is the study of the origin, evolution, distribution, and future of life in the universe. It is an inherently interdisciplinary field that encompasses astronomy, biology, geology, heliophysics, and planetary science, including complementary laboratory activities and field studies conducted in a wide range of terrestrial environments. Combining inherent scientific interest and public appeal, the search for life in the solar system and beyond provides a scientific rationale for many current and future activities carried out by the National Aeronautics and Science Administration (NASA) and other national and international agencies and organizations.

In 2017, Congress directed NASA to enter into an arrangement with the National Academies of Sciences, Engineering, and Medicine to develop a science strategy for astrobiology that would outline key scientific questions, identify the most promising research in the field, and indicate the extent to which the mission priorities in existing decadal surveys address the search for life's origin, evolution, distribution, and future in the universe (see Appendix A). In response to this congressional mandate, NASA's associate administrator for the Science Mission Directorate approached the Space Studies Board (SSB) with a request to carry out this study (Appendix B). While retaining the core language of the law, the statement of task ultimately agreed upon between SSB and NASA incorporated additional tasks relating to the specific programmatic and scientific context of the agency's various astrobiology-related endeavors, which are most prominently detailed in the 2015 NASA Astrobiology Strategy.[1] Indeed, both the SSB and NASA regarded the nature and timing of the request to be particularly fortuitous in that the results of the study would provide important input to the next decadal surveys in astronomy and astrophysics and planetary sciences, due to start in 2018 and 2020, respectively. Doubly fortuitous was the fact that the same congressional language also mandated a similar strategy to be developed for exoplanet exploration. Given close scientific ties between the astrobiology and exoplanet community, as well as the parallel timelines of the dual studies, the SSB and NASA agreed that the astrobiology and exoplanet committees should collaborate to the maximum degree feasible.

The discussions between NASA and the National Academies on the details of the task to be undertaken by the SSB converged on the following charge:

> In preparation for and as an input to the upcoming decadal surveys in astronomy and astrophysics and planetary science, the National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee to carry out a study of the state of the science of astrobiology as it relates to the search for life in the solar system and extrasolar planetary systems. The study will have the following objectives:
>
> - Take account of and build on NASA's current Astrobiology Strategy 2015;
> - Outline key scientific questions and technology challenges in astrobiology, particularly as they pertain to the search for life in the solar system and extrasolar planetary systems;
> - Identify the most promising key research goals in the field of the search for signs of life in which progress is likely in the next 20 years;
> - Discuss which of the key goals could be addressed by U.S. and international space missions and ground telescopes in operation or in development;

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[1] NASA, *NASA Astrobiology Strategy 2015*, https://nai.nasa.gov/media/medialibrary/2016/04/NASA_Astrobiology_Strategy_2015_FINAL_041216.pdf.

- Discuss how to expand partnerships (interagency, international and public/private) in furthering the study of life's origin, evolution, distribution, and future in the universe;
- Make recommendations for advancing the research, obtaining the measurements, and realizing NASA's goal to search for signs of life in the universe

> In the course of conducting this study, the committee will consider and regularly consult with the concurrent study "Exoplanet Science Strategy," in the area of assessing habitability, searching for signs of life, and other relevant areas of scientific overlap. Also the committee will not revisit or redefine the scientific priorities or mission recommendations from previous decadal surveys.

To address this statement of task, the National Academies formally established the Committee on the Astrobiology Science Strategy for the Search for Life in the Universe in the fall of 2017. The committee held its first meeting at the National Academies' Beckman Center in Irvine, California, on January 16-18, 2018. Subsequent meetings were held in Washington, D.C., at the National Academy of Sciences and the Keck Center on March 6-8 and April 25-27. A complete draft of the committee's report was sent to external reviewers for comment on [DATE]. A revised draft was assembled in [DATE] and was approved for release by the National Academies on [DATE].

In addition, the committee solicited community input in the form of white papers (see Appendix C). A total of 53 white papers originating from members of academia, employees of the federal government, and members of the general public were received and considered by the committee.

The astrobiology committee was able to have a significant degree of engagement and coordination with the exoplanet committee during the study. A co-chair of the exoplanet committee attended the first meeting of the astrobiology committee. Subsequently, a joint session of both committees was held on March 7, 2017, during the astrobiology committee's second and the exoplanet committee's first meeting. In addition, one member of the astrobiology committee also served as a member of the exoplanet committee, and SSB staff associated with the study attended the meetings of both committees. Furthermore, a working group composed of four members of each committee held three closed-session teleconferences to exchange ideas and review relevant parts of each report.

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report: John Baross, University of Washington; Courtney Dressing, University of California, Berkeley; Colin Goldblatt, University of Victoria, Canada; Martha Grover, Georgia Institute of Technology; Jonathan Lunine, NAS,[2] Cornell University; Paul Mahaffy, NASA Goddard Space Flight Center; John Rummel, SETI Institute; Gary Ruvkun, NAS/NAM,[3] Harvard Medical School, Massachusetts General Hospital; and Norman H. Sleep, NAS, Stanford University.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Louis J. Lanzerotti, New Jersey Institute of Technology. He was responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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[2] NAS, Member, National Academy of Sciences.

[3] NAM, Member, National Academy of Medicine.

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APPENDIXES

Summary

Astrobiology is a field of rapid change. In the 3 years since publication of NASA's Astrobiology Strategy 2015,[1] significant scientific, technological, and programmatic advances in the quest for life beyond Earth have taken place. Scientific advances have revolutionized fields of astrobiological study, ranging from results from missions focused on exoplanets, such as Kepler, to continuing discoveries from existing planetary missions. Returned results have changed how problems are thought of and integrated across astrobiological disciplines. From biology (e.g., miniaturized nucleic acid detection devices) to astronomy (e.g., continued improvement of starlight suppression technologies), technological advances in life detection instrumentation have continued, but will need to accelerate to match the rate of scientific advancement. Simultaneously, programmatic advances—for example, the creation of research coordination networks—have begun to break down traditional disciplinary boundaries and resulted in greater communication across the broad fields of astrobiological research.

Against the backdrop of these changes, increasing public interest in astrobiology, and the approaching decadal surveys in astronomy and astrophysics and planetary sciences, which will guide agency scientific priorities for the coming decade, NASA's request for this assessment of advances and future directions in the field of astrobiology is timely. The committee's statement of task was to build on the foundation of the 2015 NASA Astrobiology Strategy, emphasizing key scientific discoveries, conceptual developments, and technology advances since its publication. Rather than revisiting aspects that were already well covered in that document, the committee's work focused on additional insights from recent advances in the field—intellectual (e.g., conceptual insights and frameworks, modelling), empirical (e.g., observations, discoveries, novel technologies), and programmatic. This approach highlights areas of rapid scientific and technological growth and advancement that have occurred since the 2015 publication, raising key scientific questions and identifying technologies that are emerging and likely to shape the field in the coming two decades. Further, the committee identifies the roles that near-term space missions and ground-telescope projects will play and highlights increasing opportunities for private, interagency, and international partnerships. The NASA Astrobiology Program's history and continuing success in engineering cross-divisional collaborations between Earth science, astronomy, heliophysics, and planetary science (to break down disciplinary entrenchments) bodes well for its ability to leverage such partnerships to advance the search for life.

Strong collaboration between diverse scientific communities is at the core of astrobiology. Astrobiology is inherently a systems-level science requiring contributions from a wide range of disciplines. For example, in astrobiology the "system" under study is frequently a planet with a potential (or in the case of Earth, realized) biosphere. Astrobiology seeks to understand the web of interrelationships and feedbacks between time-variable planetary processes—both physical and chemical—and the proto-biological chemical and organizational dynamics that lead to the emergence and persistence of life. Systems science provides a holistic, transdisciplinary paradigm for addressing this complexity. Although detailed mathematical modeling is not (and may never be) applied to many problems in astrobiology, most notably the emergence of life, integration across diverse and sometimes seemingly disparate disciplines is key to major progress on astrobiology's fundamental questions.

Astrobiology is usually defined as the study of the origin, evolution, distribution, and future of life in the universe. However, adopting a systems approach suggests that astrobiology system science can

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[1] NASA, *NASA Astrobiology Strategy 2015*, https://nai.nasa.gov/media/medialibrary/2016/04/NASA_Astrobiology_Strategy_2015_FINAL_041216.pdf.

be defined as the integrative study of the interactions within and between the physical, chemical, biological, geologic, planetary, and astrophysical systems as they relate to understanding how an environment transforms from non-living to living and how life and its host environment coevolve.

As the above definition suggests, a systems-level view of the emergence of life that includes its environmental context, and how life and its environment subsequently changed *together* to maintain a habitable Earth, is leading to a new view of habitability. The concept of dynamic habitability drives the insight that habitability is more appropriately thought of as a continuum—that an environment may transition from inhabitable to habitable over different spatial and temporal scales as a function of planetary and environmental evolution, the presence of life, and the feedbacks between related complex physical, chemical, and biological parameters and processes. Planetary environments that may be habitable today or in the past are not necessarily the same as those that could have fostered the emergence of life. Evidence from major transitions in environmental conditions from early Earth to today, and an understanding of how they occurred, is critical for the search for life.

A better understanding of the emerging concept of dynamic habitability will come from studying the one inhabited planet currently known—Earth. The planetary environments of early Earth that gave rise to life remain poorly constrained. A better understanding of these environments entails a “mission to early Earth.” Such a “mission” will, in the near term, integrate prebiotic chemistry, origins of life research, and early Earth planetary conditions to understand their coevolution in the context of multiple parameters (including, e.g., temperature, pressure, and pH conditions) evolving over a range of spatial and temporal scales. Projecting forward, increased understanding of dynamic habitability and how life and its environment evolved together on Earth will allow questions to be addressed concerning which elements of planetary evolution are predictable and independent of biosphere evolution; what feedbacks exist between the biosphere and geosphere, including during long periods of quiescence; and how periods of catastrophic change affect the balance of influence between planetary dynamics and the biosphere. Although the research for these basic questions is most easily carried out on Earth, the far-reaching questions to be addressed in the next two decades demonstrate that dynamic habitability and the coevolution of planets and life provide a powerful comparative foundation upon which to integrate diverse astrobiology communities focusing on Earth, the solar system, stellar astronomy, and exoplanetary systems.

> **Recommendation: NASA and other relevant agencies should catalyze research focused on emerging systems-level thinking about dynamic habitability and the coevolution of planets and life, with a focus on problems and not disciplines—that is, using and expanding successful programmatic mechanisms that foster interdisciplinary and cross-divisional collaboration.** (Chapter 2)

Understanding dynamic habitability has been furthered by recent advances in investigations of extreme life and how it interacts with its environment on Earth. Identifying life in isolated *refugia* or ephemeral habitats on Earth (e.g., in the Atacama Desert) has emphasized that habitability, rather than being a binary state, is a continuum defined over varying time and spatial scales. Increasing understanding of the habitability of saline and hypersaline environments, life’s limits in extreme environments, concurrent with the discovery of potential brines on Mars, has led to a resurgence in interest in adaptations of life to saline fluids. The recent discovery of communities existing in the subsurface of the ocean floor and continental lithosphere, away from the influence of the Sun’s energy, has provided new models for rock-hosted, chemosynthetic life that may exist on other worlds. Such subsurface communities, which often live in energy-limited environments, contrast starkly to life in energy-rich environments. Whereas “slow” life that is barely able to survive in an austere environment may be detectable because the noise level is low, “fast” life in a rich environment may be detectable because the signal is high. Assessing the relative signal-to-noise ratio of each type of population in its given environmental context would help identify corresponding biosignatures that are most relevant and distinctive. Discoveries of the role of water-rock interactions producing essential electron donors and electron acceptors (e.g., hydrogen, methane sulphate), both at high rates in high-temperature vents, and at slow rates in lower-temperature continental settings, has generated a renewed focus on how to seek for signs of subsurface life—thereby informing astrobiology investigations of the subsurface of other rocky planets (e.g., Mars), ocean or icy worlds, and beyond to exoplanets.

In sum, expanded understanding of habitability of subsurface environments, brine stability of chemosynthetic organisms, and adaptations of life to saline fluids, have widespread implications for the search for life in the solar system. Into the next two decades, continued field, laboratory, and modeling studies of these communities will address the following questions:

- How does subsurface life adapt to extreme environments and energetic spectrums?
- How do marine and continental subsurface terrestrial communities inform what chemosynthetic or rock-hosted communities on other worlds might look like?
- What is the spatial and temporal distribution of potentially habitable environments on Mars, especially in the subsurface?
- What are the chemical inventories and physical processes sustaining rock-hosted life on ocean worlds?

Recommendation: NASA's programs and missions should reflect a dedicated focus on research and exploration of subsurface habitability in light of recent advances demonstrating the breadth and diversity of life in Earth's subsurface, the history and nature of subsurface fluids on Mars, and potential habitats for life on ocean worlds. (Chapter 2)

The search for life beyond the solar system has seen substantial changes in the last 3 years. Since 2015, the Kepler spacecraft more than doubled the catalog of confirmed exoplanets. Thanks to extended observations during Kepler's so-called K2 mission and improvements in data analysis, its results continue to refine our knowledge of exoplanet statistics. Some of the Kepler planets fall within what is commonly considered the "habitable zone"—traditionally defined as that region around a star where an Earth-like exoplanet could support liquid water on its surface—of their host star. This discovery, coupled with estimates of the fraction of stars with rocky, habitable-zone planets, has matured the search for evidence of life beyond the solar system enough to warrant taking the next steps toward the discovery of life on exoplanets. That search will be greatly aided by future missions and the implementation of technologies currently in development. For instance, in the near to midterm, the Transiting Exoplanet Survey Satellite (TESS), the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (Ariel), and the James Webb Space Telescope (JWST) will focus on identifying and characterizing potentially habitable, transiting exoplanets. In addition, the Wide Field Infrared Survey Telescope (WFIRST) may demonstrate the coronograph technology needed for direct imaging of exoEarths. From the ground, new instruments for direct imaging (e.g., the Gemini Planet Imager) and high-resolution spectroscopy (e.g., the Magellan Planet Finding Spectrograph) and telescopes (e.g., the Thirty Meter Telescope or Giant Magellan Telescope) will complement the observations of space-based missions using direct imaging, particularly with radial velocity measurements, and atmospheric spectra. In fact, ground-based telescopes have already detected small, potentially rocky planets in the habitable-zones of M-dwarf stars.

The technologies utilized by these instruments and missions, and the near-term data on the atmospheres of rocky exoplanets that they would yield, have the potential to make possible the first observational tests of potential habitability or, perhaps, even biosignatures within the next two decades. To confidently assess these biosignatures, it will be important to also characterize the atmospheres and the full spectrum of incident radiation for exoplanets of different sizes, compositions, and stellar irradiances so that understanding of the physical and chemical processes that lead to false positives and negatives will be increased. In order to make this progress, starlight suppression technologies that are still in development, such as coronagraphs and starshades, will be essential.

Recommendation: NASA should implement high-contrast starlight suppression technologies in near-term space- and ground-based direct imaging missions. (Chapter 5)

Technology alone will not advance the search for habitable exoplanets. A better understanding of the contexts in which potentially habitable exoplanets formed, evolved, and currently exist will be needed to inform exoplanetary exploration and planet target selection. Because exoplanets coevolve with their host stars, just as Earth coevolved with the Sun, stellar activity and evolution are critically important for understanding the dynamic habitability of exoplanets. Further, the context of solar and planetary system architecture, including the distribution of small bodies and their potential for volatile delivery to exoplanets, and evolution of that architecture, are important for determining a planet's history of habitability as well as the limits on its current habitability. Such investigations will benefit from comparisons between the architecture, evolution, and coevolution of stellar and planetary dynamics in the solar system. Comparative planetology between the solar system and exoplanetary systems is a powerful approach to understanding the processes and properties that impact planetary habitability and is essential for informing experiments, modelling, and mission planning in astrobiology, and fundamentally collaborative, and therefore ideally suited to research coordination networks.

In addition, methods well suited to the analysis of data on exoplanetary systems as well as comparative planetology will increasingly move the field forward. Continued theoretical modeling of planetary environments, including model inter-comparisons, will become increasingly necessary to explore processes, interactions, and environmental outcomes and to understand habitability and biosignatures in the context of their environment. Techniques based on statistical methods, scaling laws, information theory, and probabilistic approaches currently used in other branches of science will continue to gain traction in astrobiology. Furthermore, rapid progress in the development of artificial intelligence machine learning algorithms has the potential to improve analysis of the large, complex data sets, which are increasingly common to fields related to the search for life. In the coming two decades, that search will increasingly address questions concerning the formation, evolution, and architectures of planetary systems and how these interact with their host star to sustain habitable planets—aided by evolving understandingof how planetary systems are studied and by new missions, technologies, and approaches to data set analysis.

The search and discovery of life in this solar system and beyond hinges on the ability to identify and validate signs of life. Since publication of the 2015 *NASA Astrobiology Strategy*, the field of biosignature research has advanced four major areas as follows:

1. The search for and identification of novel biosignatures, especially those that are agnostic to life's molecular makeup or metabolism (i.e., agnostic biosignatures).
2. A concerted effort to better understanding abiosignatures (signature of abiotic processes and phenomenon), in particular those that may mimic biosignatures. Critically some (but not all) abiosignatures could be false positives and some (but not all) false positives could be abiosignatures.
3. An improved understanding of which biosignatures are most likely to survive in the environment, and at what timescales of preservation.
4. The first steps toward developing a comprehensive framework that could be used to interpret potential biosignatures, abiosignatures, false positives, and false negatives, and increase confidence and consensus in interpretations.

The identification of novel and agnostic biosignatures focuses on both in situ biosignature detection and remotely sensed biosignatures. Remotely sensed agnostic biosignatures may take the form of complex chemical networks in planetary atmospheres or atmospheric disequilibria. Such potential biosignatures, although suggestive of life and worthy of follow-on investigation, may result from a wide range of abiotic and biologic processes and therefore will need to be closely evaluated in the context of their environments. Contextual information provided by exoplanet observation may include quantification of atmospheric gases, knowledge of the stellar spectral energy distribution across a broad wavelength range (including ultraviolet wavelengths), and models of gas fluxes. Having a strong characterization of exoplanet atmospheres across their range of sizes and compositions—not only those that are potentially habitable—will aide in evaluating the potential for false positives. For in situ biosignatures, agnostic and novel approaches are benefitting from, for example, the promise of current nucleic acid sequencing technology and the commercial availability of compact, low-power, RNA and DNA sequencing devices that could contribute significantly to the robustness of the current portfolio of life detection technologies. However, while current technology for DNA amplification and sequencing may be useful for in situ detection of terrestrial contamination and lifeforms that are closely related to terran life, at present, these devices are not sufficiently agnostic to the composition of an informational polymer. Over the next two decades, improvements in these areas will help address the question of how novel and/or agnostic biosignatures are identified.

> **Recommendation: The search for life beyond Earth requires more sophisticated frameworks for considering the potential for non-terran life; therefore, NASA should support research on novel and/or agnostic biosignatures.** (Chapter 4)

In addition to identifying novel and agnostic biosignatures, in the past few years, a greater emphasis has been placed on improving understanding of which biosignatures survive in the environment and how the environment may change surviving biosignatures. Record bias, preservational bias, false negatives, and false positives all play a role in biosignature detectability. There is increasing focus on understanding the range of signatures abiotic processes can produce, particularly those that might be confused with signatures of life. Ambiguous examples of early life from Earth's own stratigraphic record demonstrate that the task of achieving community consensus on a biosignature, even on Earth, can be long and arduous. Such a task would be even greater on another planetary body. Re-addressing controversial biosignatures from Earth's early sedimentary rock record can provide an important test-bed for biosignature assessment frameworks. Such biosignatures occur at the microscale, and new technologies for microscale and nanoscale analyses combining optical microscopy, Raman spectroscopy, laser-induced breakdown spectroscopy, infrared, and other interrogatory methods offer promise for advancing detection of and confidence in biosignature interpretation. Over the next two decades, the foregoing lines of research will converge to give a clearer picture of preservational biases for biosignatures, how these may result in false negatives, and which biosignatures have the highest probability for preservation and detection, and on what timescales preservation is possible or probable.

> **Recommendation: NASA should direct the community's focus to address important gaps in understanding the breadth, probability, and distinguishing environmental contexts of abiotic phenomena that mimic biosignatures.** (Chapter 4)

The potential value of a biosignature reflects not only the intrinsic value of the biosignature, but also the associated propensity for both false positives and false negatives, which together create an uncertainty and probability for detection and reliability that is unique to each biosignature. This in itself represents a fundamental problem in attaining community consensus. Thus, in the next two decades, a growing question will be how biosignature detection and interpretation can be standardized as a probabilistic outcome such that the community can agree upon the robustness of a biosignature interpretation. Resolving this challenge before potentially controversial results from missions with potential astrobiological implications are returned is particularly important.

> **Recommendation: NASA should support expanding biosignature research to addressing gaps in understanding biosignature preservation and the breadth of possible false positives and false negative signatures.** (Chapter 4)

As an important step toward these goals, a near-term, systematic re-evaluation and increased understanding of the nature and detectability of biosignatures of chemoautotrophic and subsurface life would be immensely helpful. This follows from the increasing focus on such communities, not only on Earth, but also in the search for life in other subsurfaces—both rocky planets (e.g., Mars) and ocean worlds in the solar system. Concurrent with increasing the depth and breadth of the catalog of known biosignatures, however, it will be important to establish community consensus criteria and standards by which purported biosignatures can be evaluated and verified.

> **Recommendation: NASA should support the community in developing a comprehensive framework for assessment—including the potential for abiosignatures, false positives, and false negatives—to guide testing and evaluation of in situ and remote biosignatures.** (Chapter 4)

In addition to developing the specific research and technologies, overarching programmatic advances will be important in advancing the detection of biosignatures on other planetary bodies in future astrobiology missions. Because of the inherent ambiguity in many known biosignatures, and the necessity of making multiple measurements on a sample, in situ detection of life is best advanced by integrated suites of instruments or single instruments that permit multiple analytical techniques, including non-destructive approaches, to be applied to the same materials. Of particular importance is that, when designing such suites, science requirements, rather than off-the-shelf engineering solutions or ease of implementation, remain the key decision drivers.

Given the range of new technologies that will be implemented in biosignature detection in the coming decades, it will be increasingly important to pay particular attention to ensuring the resultant instruments and suites of instruments are successfully selected and perform to an agreed upon standard that will facilitate community consensus on results. Current NASA instrument evaluation and selection policies tend to favor low technology risk, which in some cases adversely impacts scientific payoff. This inhibits development and selection of potentially game-changing life detection technologies, for example. Furthermore, because of possible ambiguity in proposer-defined instrument success criteria, there is inherent risk in using these, rather than observation and measurement validation standards established by community consensus, to propose, evaluate, and select instruments designed to detect biosignatures. Most fundamental to the success in the search for life, however, is a need for dedicated focus on astrobiology. Planning, implementation, and operations of planetary exploration missions with astrobiological objectives have tended to be more strongly defined by geological perspectives than by astrobiology-focused strategies. However, biosignature detection will require increasingly specialized instrumentation specific to astrobiological objectives, such as micro- and macroscale imaging, spectral imaging, mass spectrometry, and nucleotide sequencing.

> **Recommendation: To advance the search for life in the universe, NASA should accelerate the development and validation, in relevant environments, of mission-ready, life detection technologies. In addition, it should integrate astrobiological expertise in all mission stages—from inception and conceptualization to planning, development, and operations.** (Chapter 5)

The scientific questions and goals summarized above, the missions and technological advances that will be implemented to solve them, and those searches for life not currently engaged in by NASA, together, present immense challenges that will require partnerships with other agencies and private and international entities to address. Opportunities for such partnerships are increasing. The existence of technologies outside of the space industry—for instance, in biomedical applications and artificial intelligence—that could be used in the search for life provide prime areas for establishing partnerships with the commercial sector. Partnership models with the commercial sector do not have to be formalized, long-term agreements, but could take the form of collaborative events bringing together industry, government agency, and individual researchers. Through such events, the agency could foster increased collaboration between individual investigators and interested corporations. Philanthropic investment in the search for life, too, is increasing and not only on traditional award funding to individual investigators, but also to self-funded and crowd-funded missions that may be categorized as "high risk/high payoff."

One high-risk/high-payoff area for which philanthropic and, increasingly, international investments have entirely supported the search for life is the search for technosignatures, or the signature of technologically advanced life. International and philanthropic investment in the search for technosignatures over the last few years have greatly enhanced search capabilities, and corresponding improvements to radio and optical facilities have also benefited the scientific community. Philanthropic investments have supported the Allen Telescope Array, advances to instrumentation at the Green Bank Telescope and the Murchison Widefield Array Telescope, and the design of dedicated optical and near-infrared observatories. International facilities include, among others, the European Low Frequency Array, the Australian Murchison Widefield Array, and the recently-completed Five-hundred-meter Aperture Spherical radio Telescope (FAST) in China. Such investments have led directly to discoveries and advances in methodology for the broad scientific community, such as with the discovery of Fast Radio Bursts and with the implementation of big data analysis techniques applied to signal detection.

Sharing assets and resources for large undertakings, such as missions, is also becoming increasingly important as mission complexity increases, although barriers to effective cooperation and collaboration exist. Expensive assets and infrastructure exist within the United States but are poorly leveraged by the astrobiological community due to insufficient coordination between government agencies. Unified research strategies between relevant entities—including, but not limited to NASA, the National Science Foundation (NSF), and the National Oceanic and Atmospheric Administration (NOAA)—for conducting research in shared areas (e.g., polar regions and other difficult-to-access analog environments) and with shared infrastructure (e.g., ground- and space-based telescopes) would facilitate advances in astrobiology. Given existing government-level and international collaborative tools within NASA's Astrobiology Program, there is potential to further catalyze coordination of international research and mission planning in this area. Although not explicitly an astrobiological mission, the multidecadal Mars Sample Return mission to be undertaken by NASA and the European Space Agency is one such example. The nucleation of government-level astrobiological partnerships that has been initiated by NASA could have the potential to motivate formation of an international organization with a unified focus on solving the immense challenges of detecting and confirming evidence for life within and beyond the solar system. One possibile example discussed by the committee would be the establishment on a new international organization dedicated to the goal of supporting the development, construction, and operation of a direct-imaging space telescope capable of searching hundreds of nearby stars for possibly habitable exoEarths. Such an organization, perhaps modeled on CERN (European Organization for Nuclear Research), the European Southern Observatory, or the International Thernonuclear Experimental Reactor (ITER) Organization, might be what is required to guarantee the sustained funding required to achieve this goal over a multidecadal time scales.

In summary, the search for life beyond Earth presents many opportunities for public, private, and international partnerships, which have the potential to advance the search for life rapidly.

> **Recommendation: NASA should actively seek new mechanisms to reduce the barriers to collaboration with private and philanthropic entities, and with international space agencies, to achieve its objective of searching for life in the universe.** (Chapter 7)

1

The Search for Life in the Universe: Past, Present, and Future

Are we alone in the universe? Sages and scientists, philosophers and poets have posed variants of this question since time immemorial. Today, we are formulating research programs that may someday provide an answer. We are in this enviable position thanks to the intertwining of three scientific and associated technological threads developed over the past 400 years.

- *Astronomical sciences*—The era of modern astronomy began in the 16th and 17th centuries when Copernicus, Brahe, Galileo, and Kepler enabled the delineation of orbits of planets and satellites in the solar system. Today, their successors are doing the same for planets orbiting other stars (exoplanets). Moreover, astronomers have shown that the elements required for life (e.g., carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur) are present across our galaxy and countless others, raising the possibility not only for habitable environments beyond the solar system, but also for life itself.
- *Geological sciences*—Development of the theory of uniformitarianism by Hutton and Playfair at the end of the 18th century began a revolution in our understanding of Earth's structure, evolution, and age. Today, techniques such as isotopic dating, electron microscopic imaging, and seismological analysis, coupled to theories such as plate tectonics, have produced a deep understanding of the nature of Earth as a planet while continuing to uncover new insights and frontiers. With the coming of the space age, geologists began applying knowledge gained from study of Earth to other bodies in the solar system. This has evolved into an interdisciplinary quest to evaluate the habitability of bodies both in this solar system and in planetary systems around other stars.
- *Biological sciences*—The twin 19th-century developments of Darwin's theory of evolution and Mendel's of genetics, coupled to the contemporaneous microbiological insights of Pasteur, brought understanding of the nature of life on Earth into the modern age. In the early-20th century, Haldane and Oparin independently proposed that the origin of life was a natural consequence of environmental conditions on the early Earth—an idea later supported by the experiments of Miller and Urey. The last half of the 20th century saw a revolution in the understanding of biological systems exemplified by the deciphering of the genetic code and the discovery of the three domains of life. The discovery of deep-sea hydrothermal vents and their associated ecosystems, powered by chemical reactions, suggested new venues for life's origins and novel habitable zones in Earth's subsurface, while advances in biotechnology provided new approaches to life detection.

THE SPACE AGE, PLANETARY SCIENCE, EXOBIOLOGY AND THE ORIGINS OF ASTROBIOLOGY

The development of robust space technologies in the second half of the 20th century catalyzed the cross-fertilization of ideas from astronomy, geology, and biology and their application to the search for habitable environments and life beyond Earth. The first international conference on the origins of life took place in Moscow in 1957, the same year as the launch of the first artificial satellite. Astronomers, geologists, biologists, and others rapidly saw the potential of access to space as a new venue for research. Astronomers would no longer be restricted to observing only at those wavelengths that penetrate Earth's blurring atmosphere. Planetary geologists could study extraterrestrial bodies up close rather than from afar. Similarly, some biologists saw space as a place to test ideas about prebiotic chemistry and the origins of life.

The founding of the Committee on Space Research (COSPAR), NASA, and the Space Science Board (SSB) of the National Academies of Sciences, Engineering, and Medicine in 1958 accelerated the creation of a multidisciplinary space science community. Planetary science had already developing a distinct, multidisciplinary identity of its own by this time. In 1959, astronomer Gerard Kuiper went to the University of Arizona to found the Lunar Laboratory (eventually, the Lunar and Planetary Laboratory/Department of Planetary Science), separate from the departments of astronomy and geology. In the same year, astrophysicist Thomas Gold went to Cornell University to establish the Center for Radiophysics and Space Research to do planetary science and ionospheric research separate from an astronomy department. Just a few years later, planetary science was established at the California Institute of Technology by geologist Robert Sharp, transforming the Division of Geological Sciences into the Division of Geological and Planetary Sciences.

NASA, in particular, was seeking experiments for its spaceflight missions. Bodies such as the SSB were keen to provide NASA with advice. COSPAR and other scientific organizations provided venues at which members of the international space science community could exchange ideas. At about the same time as the planetary science community was developing its own distinct identity, Joshua Lederberg and other like-minded researchers interested in the search for life beyond Earth soon banded together to establish the new scientific discipline of exobiology

NASA funded its first exobiology project in 1959 and established an Exobiology Program the following year. In response to a request from NASA, the SSB published an extensive series of reports on life in the universe (Table 1.1). The first report (NRC 1966) concluded that

> The biological exploration of Mars is a scientific undertaking of the greatest validity and significance. Its realization will be a milestone in the history of human achievement. Its importance and the consequences for biology justify the highest priority among scientific objectives in space—indeed in the space program as a whole. (p. 15)

The SSB's report called for the development and launch of an Automated Biological Laboratory (ABL) to Mars as early as 1971.

NASA's implementation of the ABL recommendation took the form of the twin Viking lander/orbiters to Mars in 1975. Each Viking lander carried a comprehensive suite of scientific instruments, including three specifically designed to search for signs of martian life. While both landers and orbiters were great scientific successes, they proved to be a programmatic dead end. The failure of the Viking gas chromatograph-mass spectrometer to find organics in the martian soil, coupled to generally ambiguous results of the life detection experiments, led most in the community to conclude that there was not evidence of life on Mars. Viking's perceived failure set back exploration of the Red Planet by two decades.

The early 1990s were not a happy time for NASA. The agency suffered a series of budget cuts. The mirror of the Hubble Space Telescope (HST) was flawed. Major missions in development were descoped (e.g., Cassini) and others cancelled outright (e.g., the Comet Rendezvous/Asteroid Flyby). Moreover, in 1993 Mars Observer was lost 3 days prior to entering orbit. Just a few years however, later space science discoveries began to make headlines on an almost weekly basis. Late 1995 and the first half of 1996 were particularly notable for the following news stories (Ehrenfreud et al. 2004, p. 452):

TABLE 1.1 Selected Reports by the National Academies on the Search for Life in the Solar System and Beyond

	Title	**Notes**
1966	*Biology and the Exploration of Mars*	Highlighted the biological importance of Mars exploration and recommended spacecraft missions focusing on biology
1977	*Post-Viking Biological Investigations of Mars*	Assessed results from the Viking landers and recommended that future “detailed biological studies . . . be conducted on samples returned to Earth.”
1990	*The Search for Life’s Origins: Progress and Future Directions in Planetary Biology and Chemical Evolution*	A comprehensive review of theories of and venues for the origin of life and strategies for detecting life in the solar system and beyond (including a discussion of technosignatures).
1994	*An Integrated Strategy for Planetary Sciences: 1995-2010*	Highlights the importance of the search for the origins of life and the study and characterization of exoplanets.
2001	*Astronomy and Astrophysics in the New Millennium*	First astronomy decadal survey to mention exo/astrobiology and recognize the search for life as a key strategy for addressing “the fundamental goal of astronomy and astrophysics.”
2002	*Signs of Life*	A wide-ranging examination of biosignatures and techniques used to measure biosignatures.
2003	*New Frontiers in the Solar System*	Highlighted the role astrobiology in providing “common thread for [addressing] some of the most exciting intellectual questions of our time . . .”
2005	*The Astrophysical Context for Life*	A review and assessment of the role played by astronomy and astrophysics in addressing the goals of astrobiology.
2007	*An Astrobiology Strategy for the Exploration of Mars*	An in-depth review of Mars as an abode of past and/or present life and strategies for its future study.
2007	*The Limits of Organic Life in Planetary Systems*	An initial examination of the possibility of non-terran life (i.e., life as we do not know it), its nature, and detectability.
2010	*New Worlds, New Horizons in Astronomy and Astrophysics*	One of three primary scientific objectives is seeking hahabitable planets
2011	*Vision and Voyages for the Planetary Sciences in the Decade 2013-2022*	One of three scientific themes is exploring planetary habitats. Recommends spacecraft missions to explore astrobiologically significant environments on Mars, Europa, and Enceladus.
2017	*Searching for Life Across Space and Time*	The proceedings of a workshop highlighting the current understanding of biosignatures detectable via in situ and remote-sensing techniques.

- Identification of the first confirmed exoplanets;
- Results from NASA's Galileo spacecraft suggesting that a liquid water ocean existed below the icy surface of Jupiter's satellite, Europa;
- Discovery of the extent of Antarctica's Lake Vostok and the realization that it was a terrestrial analog of a potentially habitable extraterrestrial environment;
- Observations of protoplanetary disks with the newly repaired HST; and
- Discoveries of the diversity of novel microbial lifeforms existing in extreme terrestrial environments.

The pace of popular interest in space-related activities reached a peak with the publication of a paper suggesting the presence of microbial fossils in the martian meteorite ALH84001. Although subsequent scientific analyses did not substantiate this claim, the wave of public interest in topics relating to the possibility of life beyond the Earth reached to the highest levels. Most notably, President Clinton responded by supporting a congressional call for a "Space Summit." Such a summit would

> Allow the Administration to work with congressional leadership to develop a broad consensus on a balanced NASA program for the future . . . [and] provide an opportunity to discuss the recent evidence that life may have existed on Mars, as well as other significant advances in space science and technology. (Gibbons 1996)

In preparation for the summit, the SSB organized a workshop in October 1996 to discuss the implications of ALH84001 and other recent scientific advances relating to the search for the origins of life, planetary systems, stars, galaxies, and the universe (Ehrenfreud et al. 2004, p. 453). Key participants in the workshop subsequently briefed Vice President Gore on the workshop's key finding that recent "breakthroughs are astonishing returns being reaped from years of investments in many science disciplines. Now is the time to leverage that investment and pursue the quest for origins into the 21st Century" (Canizaris et al.,1996).

The outcome of these high-level discussions came a few months later with the inclusion of the "Origins Initiative" in the administration's fiscal year 1998 budget proposal for NASA. In addition to the inclusion of significant funding increases for spacecraft missions in astrophysics and planetary science (particularly for Mars and Europa), the billion-dollar initiative included the establishment of a new program in astrobiology. The Astrobiology Program would subsume the existing Exobiology Program and have as its initial central feature the founding of a NASA Astrobiology Institute.

ASTROBIOLOGY ROADMAPS AND STRATEGIES

The 1998, 2003, and 2008 Astrobiology Roadmaps

Soon after the establishment of the NASA Astrobiology Institute (NAI) in 1998, work began on the drafting of the first astrobiology roadmap. The purpose of this document was to provide guidance for research and technology development relevant to astrobiology across NASA's space and Earth science programs, as well as its human spaceflight program. More specifically, it was to provide a scientific framework for the nascent NAI and to serve as a reference for NASA astrobiology funding opportunities more generally. The following three fundamental questions formed the roadmap's foundations (NASA 1998):

- How does life begin and evolve?
- Does life exist elsewhere in the universe?
- What is life's future on Earth and beyond?

Since all three questions represented long-term aspirations rather than issues addressable in the near-to-mid-term, the roadmap presented a series of 10 more specific goals.

The 1998 roadmap underwent a complete revision in 2003. The 2003 Roadmap was narrower in scope than its predecessor, particularly in its focus on microbial life and its elimination of objectives concerning human spaceflight. It retained the three fundamental questions, reduced the number of goals to seven, and provided details regarding those goals in 18 specific objectives. The 1998 roadmap was distributed by NASA via the Internet and in informal media. The 2003 and 2008 roadmaps were published as articles in the journal *Astrobiology* (Des Marais et al. 2003, 2008).

The 2015 Astrobiology Strategy

In 2013, NASA initiated an ambitious activity to revise and extend the Astrobiology Roadmap. Through a series of in-person and virtual meetings, NASA and its contractor, Knowinnovation,[1] collated and combined input from 100-plus leading members of the astrobiology community to create the 2015 Astrobiology Strategy (NASA 2015; hereafter referred to as the 2015 Astrobiology Strategy).

Unlike the preceding astrobiology roadmaps, the 2015 Astrobiology Strategy was organized around a series of major research themes spanning astrobiology, as follows:

- Identifying abiotic sources of organic compounds;
- Synthesis and function of macromolecules in the origin of life;
- Early life and increasing complexity;
- Coevolution of life and the physical environment;
- Identifying, exploring, and characterizing environments for habitability and biosignatures; and
- Constructing habitable worlds.

The current committee’s statement of task was to take the 2015 Astrobiology Strategy as its starting point and build on its foundation, emphasizing key scientific discoveries, conceptual developments, and technology advances since its publication. Rather than revisiting aspects that were already well covered in the existing document, the committee’s work necessarily focused on additional insights from recent advances in the field—intellectual (e.g., conceptual insights and frameworks, modelling), empirical (e.g., observations, discoveries, novel technologies), and programmatic. Therefore, it is useful to examine each of the 2015 Astrobiology Strategy research themes in more detail because they and the key questions deriving from them are revisited and built on in subsequent chapters.

Identifying Abiotic Sources of Organic Compounds

The key research areas identified within the 2015 Astrobiology Strategy’s thematic area on identifying abiotic sources of organic compounds are as follows:

- What were the sources, activities, and fates of organic compounds on the prebiotic Earth?
- What is the role of the environment in the production of organic molecules?
- What is the role of the environment on the stability and accumulation of organic molecules?
- What constraints can the rock record place on the environments and abiotic reactions of the early Earth?

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[1] See http://knowinnovation.com.

Synthesis and Function of Macromolecules in the Origin of Life

The key research areas identified within the 2015 Astrobiology Strategy's thematic area on the synthesis and function of macromolecules in the origin of life are as follows:

- What is the chemistry of macromolecular formation reactions?
- How does information transmission and chemical evolution occur?
- What are the chemical alternatives? How and why do they occur?
- What is the role of environment?
- Macromolecular function—how did physicochemical effects develop over time?
- What are the advanced steps of macromolecular function?
- What led to macromolecular complexity?

Early Life and Increasing Complexity

The key research areas identified within the 2015 Astrobiology Strategy's thematic area on early life and increasing complexity are as follows:

- Origin and dynamics of evolutionary processes in living systems—theoretical considerations;
- Fundamental innovations in earliest life;
- Genomic, metabolic, and ecological attributes of life at the root of the evolutionary tree;
- Dynamics of the subsequent evolution of life; and
- Common attributes of living systems on Earth.

Coevolution of Life and the Physical Environment

The key research areas identified within the 2015 Astrobiology Strategy's thematic area on the coevolution of life and the physical environment are as follows:

- How does the story of Earth—its past, present, and future—inform us about how the climates, atmospheric compositions, interiors, and biospheres of planets can coevolve?
- How do the interactions between life and its local environment inform our understanding of biological and geochemical coevolutionary dynamics?
- How does our ignorance about microbial life on Earth hinder our understanding of the limits of life?

Habitability and Biosignatures

The key research areas identified within the 2015 Astrobiology Strategy's thematic area on identifying, exploring, and characterizing environments for habitability and biosignatures are as follows:

- How can we assess habitability on different scales?
- How can we enhance the utility of biosignatures to search for life in the solar system and beyond?
- How can we identify habitable environments and search for life within the solar system?
- How can we identify habitable planets and search for life beyond the solar system?

Constructing Habitable Worlds

The key research areas identified within the 2015 Astrobiology Strategy's thematic area on constructing habitable worlds are as follows:

- What are the fundamental ingredients and processes that define a habitable environment?
- What are the exogenic factors in the formation of a habitable planet?
- What does Earth tell us about general properties of habitability (and what is missing)?
- What are the processes on other types of planets that could create habitable niches?
- How does habitability change through time?

FORWARD FROM NASA'S ASTROBIOLOGY STRATEGY 2015

The 3 years between the publication of the 2015 Astrobiology Strategy and drafting of the current report has seen significant scientific, technological, and programmatic advances in the quest for life beyond Earth. For example, in January 2015, the Kepler spacecraft had identified about 1,000 confirmed exoplanets and its follow-on mission, the Transiting Exoplanet Survey Satellite (TESS), was still in development. Today, Kepler's observations have confirmed the existence of some 2,600 exoplanets, and TESS is now in orbit. These discoveries include complex multiplanet systems and Earth-size bodies. Closer to home, small particles of silica and molecular hydrogen have been observed within the plume of material emenating from the south pole of Enceladus, suggesting ongoing hydrothermal activity on this moon of Saturn. Similarly, strong seasonal variations in the trace amounts of methane observed in the martian atmosphere provide tantalizing hints about possible biological or geologic activity on Mars. While on Earth, the studies of the noble gas components in subsurface waters has demonstrated that such aqueous environments can be preserved on billion year timescale. The preservation of a habitable environment on Earth and by extension to all rocky planets for a billion years or more has major implications for the search for life in the solar system and beyond.

> **Finding:** Given the considerable rate of advancement in astrobiological science since the 2015 NASA Astrobiology Strategy was published, significant strategy updates and new discoveries can be addressed in this report.

Against the backdrop of these and other rapid advances, Congress directed NASA (see Appendix A) to enter into an arrangement with the National Academies of Sciences, Engineering, and Medicine to develop a science strategy for astrobiology to address the search for life's origin, evolution, distribution, and future in the universe. In response to the congressional mandate, NASA's associate administrator for the Science Mission Directorate approached the Space Studies Board (SSB) with a request to carry out this study (Appendix B).

ASTROBIOLOGY: A SYSTEMS-LEVEL SCIENCE

It is often said that astrobiology is a highly interdisciplinary science, but this simple statement may not fully capture the degree to which the field requires integration and synthesis of an enormous range of subject matters and disciplines including application across deep time. The search for life in the universe requires a rigorous open mindedness, constant questioning of paradigms, and nimble reevaluation of criteria and search strategies in response to intellectual innovation and conceptual advances, and technological advances and discoveries both expected and unanticipated. For example, the origin of life is one of the most profound questions addressed by astrobiology. Research on this question frequently takes the form of "bottom-up" investigations, which focus on prebiotic synthesis in various plausible early Earth environments that lead to the molecules necessary for life's emergence. Alternatively, research in this area is "top-down" and focuses on the emergence of the most fundamental aspects of extant life, such as the genetic code and the assembly of primitive enzymes. Yet understanding the prebiotic pathways that led to life's emergence on Earth is only one aspect of the more universal search for life through both time and space. That endeavor requires more cross-cutting research that focuses not only on life itself, but also on the role life plays in evolving planetary processes and how these processes in turn influence the evolution of life—for example, by providing access to chemical pathways that dissipate planetary-scale, time-dependent variations in heat, enthalpy, and entropy (i.e., thermodynamic disequilibrium). Further, to extend the study of the origin of life to celestial bodies beyond Earth, these perspectives require careful integration with inferences about the environments and conditions that may have existed on extraterrestrial bodies both within and beyond the solar system at any putative time when life may have arisen. Finally, emergence-of-life studies are also concerned with understanding how such life might have left its signature.

Studies such as these require not only the coming together of scientists from an extraordinarily wide range of disciplines, but also a true synthesis of their varied perspectives and approaches to produce a model describing both processes and products that are as complete as possible. Such models also need to satisfy the scientific criteria of experimentation, form testable hypotheses, allow modification of hypotheses based on observation and measurement, and forward predictive power. Astrobiology is thus inherently a systems-level science in which an integrated view across many disciplines is essential for major progress on fundamental questions.

> Life affects its Environment. At the same time, the Environment affects Life.
>
> (NASA 2015)

Visions and Voyages for Planetary Science in the Decade 2013-2022 (NRC 2011a) captured much of this by identifying the necessity in understanding how the myriad chemical and physical processes that define the solar system, and specifically planetary formation, and evolve over time to impact habitability and the potential for life. This report extends that thinking a step further and emphasizes the coevolution of planetary bodies and life, both in the solar system and beyond. Systems science is a holistic approach to a problem that considers as many of the constituent parts and dynamics of the system as is possible. There are many pertinent examples for astrobiology. For the study of the origin of life, this approach derives information from preexisting conditions, the interplay of the planetary and chemical environment, and the subsequent coevolution of life and the environment. For the exploration of planets, systems science approaches offer the chance to better select landing sites by, for instance, evaluating how an environment may have sustained life over long timescales and concentrated evidence of that life in the rock record. For exoplanets, such an approach enables an assessment of how a given atmospheric signature is related to the planet and potential biosphere, given the multiple potential sources that may have given rise to that gas. As an example, methane is produced by geological processes as well as living systems, and oxygen can be produced photochemically in atmospheres without biogenic sources of oxygen.

The 2015 Astrobiology Strategy emphasized the evolution of astrobiology to more effectively link "astro" and "life," in the sense that the intersection of life and environment is what makes a planetary body habitable. The coevolution of life and the physical and chemical environment is a core feature of astrobiology.

> **Finding:** Astrobiology system science is the integrative study of the interactions within and between the physical, chemical, biological, geologic, planetary, and astrophysical systems as they relate to understanding how an environment transforms from non-living to living and how life and its host environment coevolve.

Organization of This Report

Coevolution of life and its physical environment is indeed a powerful lens and strategy for investigation of the origin of life, for understanding early Earth and the evolution of life on Earth, for the search for life, and for the characterization of habitable environments and search for life in the solar system and beyond. The committee's charge is to take account of and build on NASA's current 2015 Astrobiology Strategy and outline key scientific questions and technology challenges in astrobiology in the light of recent discoveries and conceptual development and models. To address this charge, a considerable amount of space (the next three chapters) is devoted to a systems-science approach to the major developments in key scientific questions and challenges in the context of three evolving conceptual frameworks.

- Chapter 2 is organized around the concept of dynamic habitability; that is, the habitability of an environment is not a binary (yes/no) characteristic but is a continuum that evolves over time.
- Chapter 3 is devoted to comparative planetology and multi-parameter habitability assessment.
- Chapter 4 discusses the identification and interpretation of biosignatures.

In each of these three chapters, the committee has outlined areas where significant scientific progress has been made in the last few years and has led to new understanding and the formulation of new questions and/or research themes not addressed in, or substantially developed since, the 2015 Astrobiology Strategy. Please note that in Chapter 3, rather than the traditional separate treatment of in situ and remote-sensing techniques, the committee has endeavored to integrate the discussion of in situ and remote-sensing, despite that fact this attempt to break down barriers between different communities and their favorite techniques may introduce some unavoidable duplication of material.

The remaining chapters are organized as follows:

- Chapter 5 illustrates how the systems science approach to astrobiology developed in Chapters 2, 3, and 4 is supported and contextualized within a dynamic and evolving technology and programmatic landscape.
- Chapter 6 integrates the advances and opportunities in Chapter 5 to identify the most promising key research goals in the field of the search for signs of life in which progress is likely in the next 20 years and to discuss which of the key goals can be addressed by U.S. and international space missions and ground telescopes in operation or in development.
- Chapter 7 contains a discussion of how expanded partnerships—for example, interagency, international and public/private—can further the study of life's origin, evolution, distribution, and future in the universe.

For readers interested in the committee's responses to specific aspects of its charge, the committee offers the following mapping:

- Take account of and build on NASA's current 2015 Astrobiology Strategy (see Chapter 1).
- Outline key scientific questions and technology challenges in astrobiology, particularly as they pertain to the search for life in the solar system and extrasolar planetary systems (see Chapters 2, 3, 4 and 5).
- Identify the most promising key research goals in the field of the search for signs of life in which progress is likely in the next 20 years (see Chapter 6).
- Discuss which of the key goals could be addressed by U.S. and international space missions and ground telescopes in operation or in development (see Chapter 6).

- Discuss how to expand partnerships (interagency, international and public/private) in furthering the study of life's origin, evolution, distribution, and future in the universe (see Chapter 7).
- Make recommendations for advancing the research, obtaining the measurements, and realizing NASA's goal to search for signs of life in the universe (see Chapters 2, 4, 5 and 7).

The committee notes that achieving a clean mapping between specific aspects of the charge (e.g., bullet items 3 and 4) necessitated the repetition of some material from Chapters 2, 3, 4, and 5 in Chapter 6. The committee believes that such repetition is acceptable and appropriate because the average reader is more likely to be interested in the committee's views on a specific topic than they are to read the report from cover to cover.

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2

Dynamic Habitalility

Earth remains our only reference point for an inhabited world. The field of astrobiology, however, seeks to differentiate between the specific requirements for life on Earth (terran life; Box 2.1) and conditions on other planets that might enable and promote the emergence and persistence of life. Therefore, astrobiology distills what we know of terran life and its origins on early Earth into the broad planetary conditions necessary for the emergence and proliferation of life and the rise and evolution of its biosignatures. Ideally, those conditions identified are general enough to apply across various types of celestial bodies (rocky planets, icy moons, small bodies, or exoplanets) but also specific enough to provide useful search and discovery tools.

This chapter focuses on the generalized planetary conditions and characteristics that are thought to support the emergence of life and its persistence through time. In the spirit of systems science, these conditions arise from the fundamental and broadly applicable principles of thermodynamics. In addition to advancing a thermodynamic perspective on life's origins, this chapter also explores the nature and extent of extant life and how these have influenced the recent focus on the concept of dynamic habitability (Box 2.2). Finally, this chapter demonstrates how biological ecosystems coevolve with key aspects of planetary dynamics and evolution and suggests that this coevolution might either encourage or inhibit life's emergence.

BOX 2.1
Life as We Know It

Earth, or terran, life (i.e., life as we know it) uses a variety of energy sources (e.g., solar, geothermal, or chemical) to maintain itself in a state of thermodynamic disequilibrium. Terran life is based on carbon (plus hydrogen, nitrogen, oxygen, phosphorous, and sulfur) and readily maintains covalent bonds. On Earth, water is the liquid medium of choice used to facilitate biochemical reactions and nutrient transport; hence NASA's "follow the water" strategy in the search for life and habitable environments. Finally, all known life on Earth uses DNA as the basis of a molecular system enabling Darwinian evolution.

Applying life's characteristics to the search for life elsewhere, however, means identifying not simply the requirements for terran life, but instead the fundamental characteristics of life. The commonly cited set of general criteria are (in decreasing order of certainty) as follows (NRC 2007):

- A means to sustain thermodynamic disequilibrium;
- An environment capable of maintaining covalent bonds, especially between carbon, hydrogen, and other atoms;
- A liquid environment; and
- A self-replicating molecular system that can support Darwinian evolution.

Whether or not life elsewhere in the solar system or beyond might be similar to terran life remains to be determined. Speculations abound as to whether life could be based on an element other than carbon, use a solvent other than water, or employ a different type of molecular system for encoding genetic information and facilitating evolution.

A THERMODYNAMIC PERSPECTIVE ON LIFE'S ORIGIN

The 2015 Astrobiology Strategy (NASA 2015) addresses the origin of life in a manner that dates back a century to what has become known as the Oparin-Haldane hypothesis (e.g., Chang et al. 1983). This hypothesis focuses primarily on *how* life emerged and specifically postulates that life began as a set of chemical reactions starting from relatively simple molecules produced, for example, in the atmosphere by lightning or photochemistry, in the crust by water-rock reactions, or by aqueous alteration on the parent bodies of carbonaceous meteorites. The hypothesis posits that these prebiotic molecules subsequently reacted at water-atmosphere-mineral interfaces to produce more complex molecules, polymers (covalently-bonded chains of small molecular units; for example, nucleotides polymerize to form nucleic acids, and amino acids polymerize to form proteins), and/or metabolic cycles—eventually leading to self-organized, autocatalytic protocells. (See Box 4.1 for a discussion of the role viruses may have played in the transition from abiotic to biotic processes.) The broad strokes of this paradigm are still recognizable in much of modern prebiotic chemistry, which is laid out in detail in Chapters 1 to 3 of the 2015 Astrobiology Strategy.

More recently, the conversation has shifted to investigate whether there are naturally occurring generalizable forces on a planet that, under the right circumstances, lead to life's emergence. Smith and Morowitz (2016) suggest that such planetary conditions might better elucidate *why* life arises. They hypothesize that Earth's biosphere, specifically its metabolisms, arose as a relaxation path for planetary-scale thermodynamic disequilibria that result from slow relaxation timescales in late-stage planet formation. Thus, the thermodynamic disequilibrium exhibited by the young Earth across its atmosphere, hydrosphere, and lithosphere led to the emergence of life in the form of the biosphere, or as Smith and Morowitz term it, the "fourth geosphere." Within this fourth geosphere, they argue, the ecosystem, rather than the individual organism, is the organizational level at which hierarchical controls occur. These system-level controls enable both the emergence of life and the apparent continuous existence of a terran biosphere—albeit a dynamically evolving one—over more than 4 billion years.

> **Finding:** Systems-level emergence of life research incorporating thermodynamic principles is important for understanding life as a planetary phenomenon.

A strength of the Smith and Morowitz hypothesis is that it suggests a universality of laws governing the emergence and evolution of life that transcends the manifestations of individual genomes and species. This, of course, does not guarantee that it is correct, but it represents a testable hypothesis.

Thermodynamic disequilibrium is also required to sustain life once it gets started. All known life takes advantage of thermodynamic disequilibrium that is globally powered either by incoming solar radiation or by Earth's internal radiogenic or accretionary heat. Thus, thermodynamic disequilibrium is a necessary input for life. It is, however, also a potential byproduct of life and one that evolves with changing planetary and biosphere conditions (Krissansen-Totton et al. 2018). For example, the accumulation of O_2 in Earth's atmosphere is a byproduct of oxygenic photosynthesis. (Meadows 2017). In the modern atmosphere, the coexistence of both O_2 and CH_4 produce a thermodynamic disequilibrium that is often regarded as a planetary biosignature (Simoncini et al. 2013). Although NASA funded the initial research by James Lovelock in the late-1960s and early-1970s on disequilibrium as a life-detection strategy (e.g., Hitchcock and Lovelock 1967), it is now widely accepted that atmospheric disequilibrium is not necessarily a byproduct of life. Kasting (2014) and others have pointed out that CO and H_2 are typically out of thermodynamic equilibrium in models of Earth's early atmosphere as a consequence of the production of CO from photolysis of CO_2 combined with escape of H_2 to space. The fact that thermodynamic disequilibria at varying temporal and spatial scales can give rise to life, sustain life, and also be a byproduct of life highlights the challenge of differentiating conditions that may give rise to and sustain planetary habitability and also produce biosignatures detectable on a planetary scale.

THE DYNAMIC EARLY EARTH AND LIFE'S EMERGENCE

The search for habitable worlds inevitably leads to questions of habitability on Earth—the only planet on which life certainly arose and evolved and hence an essential pillar of astrobiology research. While the extent of life on Earth knows few bounds and inhabits almost all known extreme environments, it is not clear that life's origins on this planet were as ubiquitous. A century following the Oparin-Haldane hypothesis (e.g., Chang et al. 1983), the potential chemical and environmental pathways that gave rise to life have been greatly expanded and remain hotly debated. In many cases, these evolved hypotheses bear little resemblance to the organic chemistry originally postulated, and despite decades of research, plausible prebiotic pathways within realistic early Earth environments remain elusive. One of the greatest challenges still facing the origins of life community is not only a more accurate and complete understanding of dynamic and spatially variable early Earth conditions, but also the means to faithfully represent these conditions in prebiotic chemistry experiments.

BOX 2.2
Dynamic Habitability

Habitability refers to a set of environmental conditions capable of supporting life. On a planetary scale, this most often includes the presence of liquid water, an energy source, and the availability of the basic elements of life—commonly considered to be carbon, hydrogen, nitrogen, oxygen, phosphorous, and sulfur, or CHNOPS. At smaller spatial scales, habitability is determined by ranges in temperature (T), pressure, (P) acidity (pH), and salinity as well as minimum energy requirements. The limits of habitability are generally defined by studying life as we know it, and our current understanding is largely explored either through experiments and models that investigate only a few parameters at a time or through empirical investigation of Earth's extreme environments. Habitability, however, also implies that environmental conditions are sustained such that life persists through time.

Dynamic habitability expands this conceptual framework. First, dynamic habitability recognizes that the combined effects of multiple parameters (e.g., T, P, salinity, pH) define whether or not life can emerge and persist and that while one or more parameters may vary outside the canonical limit to life, it is their combined effect that causes an environment to be habitable or not. Second, dynamic habitability acknowledges that environments—and organisms— coevolve over time.

At the planetary scale, characteristics of dynamic habitability include stellar evolution and its impact on the presence of liquid water over time; the evolving structure of the planet interior influencing, among other things, the magnetic field and plate tectonics; and the state of the atmosphere, which might, for example, redistribute sources of metabolic energy. On more local scales, dynamic habitability encompasses changing environmental conditions driven not only by planetary-scale dynamics, but also by more local processes like fluid flow and mixing or water-rock reactions, which can alter thermal and chemical gradients and therefore control not only available energy sources but also energy gradients and fluxes. Conditions of local dynamic habitability are necessarily changed by the activity of in situ life through nutrient consumption, energy transformation, cell production, and the addition of products from metabolic activity. On Earth, conditions of global habitability have been changed by life, with the most profound example being the evolution of oxygenic photosynthesis.

The earliest signs of life on Earth indicate that the prebiotic chemistry that led to life's origins most likely commenced during the Hadean Eon (prior to ~4 Gyr), which is thought to be the most dynamic period in the planet's history, but is also the period for which observations, proxies, and models are the most sparse. The earliest possible timing for sustainable prebiotic chemistry followed the moon-forming event and replacement of the magma ocean by solid crust at ~4.5 Ga (Abe 1993a; Elkins-Tanton 2008; Sleep et al. 2014; Harrison et al. 2008). In the ensuing half billion years, the onset of plate tectonics, formation of continents, and condensation of the atmosphere and oceans gave rise to the dynamic, diverse, and interconnected environments from which the chemistry that led to life's origins arose.

The temporal relationships among these transitions are crucial to accurately describing and replicating early Earth environments in the laboratory and in modelling, and yet, the timing of only a few of these events is well constrained. For example, the presence of a liquid water ocean and crustal rocks with a bulk granitoid composition by ~4.4 Ga is borne out by the chemical and isotopic signatures of the Jack Hills Hadean zircons (Wilde et al. 2001; Mojzsis et al. 2001; Watson and Harrison 2005; Harrison 2009). However, the timing of other geological processes and planetary conditions are rarely discriminated throughout the Hadean Eon. The onset of plate tectonics is thought by many geologists to have commenced prior to ~3 Ga (Condie and Kröner 2008; Dhuime et al. 2012; Korenaga 2013; Laurent et al. 2014; Dhuime et al. 2015; Condie 2016; Tang et al. 2016b; Nebel-Jacobsen et al. 2018). However, there is no consensus on this issue, nor is it clear that plate tectonics operated in the same manner as it does today. Furthermore, despite estimates of early bulk atmospheric and ocean conditions (Sleep et al. 2001; Zahnle et al. 2007; Abe et al. 2000; Kasting 2014), changes in atmospheric composition during the Hadean and Archean are less well defined. Therefore, specific and overlapping conditions are difficult to distinguish within the Hadean and early Archean. Furthermore, the broad understanding of Hadean conditions has not yet been translated to specific early Earth environments, their specific physiochemical conditions, the co-variation of these conditions, the flow dynamics, or the thermal and chemical gradients contained within them. Yet it is exactly these specific, co-varying, and dynamically interconnected environmental conditions that gave rise to life's chemistry. The global extent and temporal ambiguity of these conditions further limit the extent to which prebiotic chemistry research can truly reflect early Earth environments.

The importance of constraining environmental conditions to better characterize early Earth prebiotic chemistry is emphasized in Chapters 1 and 2 of the 2015 Astrobiology Strategy (NASA 2015), and integration of plausible early Earth conditions into prebiotic chemistry experiments is becoming more common. Prebiotic pathways constituted within complete suites of early Earth environmental conditions, however, are still out of reach. It is important that advances in understanding the abiotic inventory and baseline are grounded in understanding evolving environmental conditions over time and space. The field of prebiotic chemistry was originally bifurcated along the "genetics-first" and "metabolism-first" hypotheses (e.g., Gilbert 1986; Wachtershauser 1990), however, these often-competing hypotheses overlap in their general objective: How do abiotic synthesis reactions eventually lead to the chemistry of life? The true divergence lies in the chemical targets: Did the primitive chemistry that led to life actually consist of metabolic precursors and primitive metabolic cycles, or the nucleic acids, proteins, and lipids that now comprise the central dogma of biology?

Specifically, origins-of-life research is largely focused on the abiotic reactions that lead to the initial reduction of CO_2 to simple organic compounds, their synthesis into more complex monomers (e.g., nucleotides, amino acids) and/or metabolic precursors (e.g., pyruvate, acetic acid), and either the polymerization into functional polymers or a sequencing of reactions into prebiotic metabolic pathways. Laboratory experiments to demonstrate these processes have limited success under ideal conditions, and so the applicability of such experiments to early Earth is often limited to singular environmental parameters (e.g., mineralogy, temperature, etc.) instead of a full accounting of system-wide, co-varying conditions.

Recent investigations are targeting more plausible physicochemical conditions and sources of precursors and essential elements. For example, the role of minerals in prebiotic chemistry is a focus of much of the current experimental research. While the potential for mineral catalysis of RNA polymerization was identified early on (Ferris et al. 1996), a wide variety of minerals more representative of a heterogeneous early Earth are now considered to be important for the concentration, adsorption, alignment, and polymerization of not only RNA, but a variety of nucleic acids, amino acids, and sugars (Anizelli et al. 2015; Estrada et al. 2015; Feuillie et al. 2015; Hashizume 2015; Pandey et al. 2015; Schwaminger et al. 2015; Bhushan et al. 2016; Gregoire et al. 2016; Iqubal et al. 2016; Nitta et al. 2016; Pedreira-Segade et al. 2016; Yang et al. 2016; Biondi et al. 2017; Fuchida et al. 2017; Georgelin et al. 2017; Guo et al. 2017; Iqubal et al. 2017; Kitadai et al. 2017; Pedreira-Segade et al. 2018; Villafane-Barajas et al. 2018; Yamaguchi et al. 2018). Mineral surfaces may serve as catalysts for the initial reduction of CO_2 in both surface and subsurface environments (Varma et al. 2018; Steele et al. 2016; Braterman et al. 1983; Kim at et al. 2013; White et al. 2015; Martin et al. 2008; Herschy et al. 2014) and may give rise to biomolecular chirality (e.g., Hazen and Sverjinsky 2010; Schrader 2017). Furthermore, specific minerals (e.g., schreibersite, chimney precipitates) are being invoked either as meteoritic or terrestrial sources of phosphorus or catalysts for phosphorylation (Pasek et al. 2015; La Cruz et al. 2016; Fernandez-Garcai et al. 2017; Pasek 2017; Holm 2014; Barge et al. 2014). Phosphorus may also have been available in the highly soluble form of phosphite, generated by reduction of phosphates through its reaction with Fe(II) (Herschy et al. 2018).

In addition to the variety of mineralogies available on the early Earth, the effects of individual parameters, including pH, salinity, fluid chemistry, and pressure on a range of prebiotic processes—from CO_2 reduction to RNA polymerization—are being investigated to discriminate those physicochemical conditions that could and could not give rise to viable prebiotic chemistry (e.g., Cody et al. 2000; Lazar et al. 2015; Hazen et al. 2002; Kitadai et al. 2017; Pedreira-Segade et al. 2016; Pedreira-Segade et al. 2018; DaSilva et al. 2015; Nitta et al. 2016; Dalai et al. 2018; Maurer and Nguyen 2016; Maurer 2017). Even more traditional prebiotic synthesis experiments strive to identify precursors that are plausible for early Earth (e.g., Bada et al. 2016; Cafferty et al. 2016a; Powner et al. 2009; Sutherland 2016). In addition to system components, specific dynamics within geologic environments—including flow, mixing, and freeze-thaw and wet-dry cycles that concentrate and dilute solutions—are gaining prominence as important considerations for nucleotide formation, peptide and nucleic acid polymerization, and the rise of metabolic cycles (Forsythe et al. 2015; Damer and Deamer 2015; Ross and Deamer 2016; Ritson et al. 2018; McGlynn et al. 2012; Burcar et al. 2015; Baaske et al. 2007). Further, ultraviolet radiation is more commonly integrated into prebiotic synthesis experiments, bringing renewed interest to hypotheses about a surface emergence of life (e.g., Nuevo et al. 2012; Ritson et al. 2018; Patel et al., 2015, Fornaro et al. 2013; Bacchus-Montabonel 2013; Powner and Sasselov 2016; Benner et al. 2010; and Pearce et al. 2017).

While formerly associated solely with the metabolism-first theory, the role that both marine and continental hydrothermal systems may play in the origin of life (Corliss 1990), and specifically, in the formation, concentration, and polymerization of RNA (Milshteyn et al. 2018; Burcar et al. 2015; DaSilva et al. 2015; McGlynn et al. 2012; Damer and Deamer 2015), amino acids (Fuchida and Masuda 2015; Kitadai 2015; Zhang et al. 2017; Estrada et al. 2017), and other prebiotic scenarios (Yang et al. 2018; Niether et al. 2016; Damer and Deamer 2015) is becoming more widely considered. Of particular interest is the combination of physical and chemical parameters that produce thermal, pH, and other chemical gradients along with pore spaces that can drive chemical differentiation (Agerschou et al. 2017; Baaske et al. 2007; Keil et al. 2016; Kreysing et al. 2015; Möller et al. 2017; Herschy et al. 2014; Barge et al. 2014). Outside of the environmental parameters, alternative and multicomponent, multipolymer chemistries and processes are also challenging more long-established hypotheses and inspiring innovative research avenues (Jauker et al. 2015; Sproul 2015; Cafferty et al. 2016b; Griesser et al. 2017; Patel et al. 2015; Caetano-Anollés and Seufferheld 2013). Finally, the production of biotic precursors, specifically through proto-metabolic pathways during water-rock reactions, are reinvigorating ideas about the rise of metabolism (McGlynn et al. 2012; McDermott et al. 2015; Herschy et al. 2014; Varma et al. 2018; Westall 2018). The chemistry of reductive homologation of hydrogen cyanide and other nitriles has been experimentally demonstrated to produce precursors of ribonucleotides, amino acids, and lipids. In this hypothesis, all necessary cellular subsystems could have arisen simultaneously through a common chemistry in reactions which require ultraviolet light and use hydrogen sulfide as the reductant (e.g., Powner et al. 2009; Patel et al. 2015). Sutherland, Powner, and colleagues continue to explore nitrile chemistry in holistic, systems approaches to the generation of all prebiotically important compound classes (Sutherland 2016; Islam and Powner 2017) advancing the early ideas of Oro (1960) and elaborated by Eschenmoser (2007). A similar systems approach is needed to explore various potential pathways that lead from chemistry to biology (Szostak 2017). Various elements, including divalent metal cations and iron-sulfur clusters, could have assisted in these prebiotic reactions and served as cofactors for the earliest catalysts.

Incongruities between experimental conditions and realistic early Earth parameters still chellenge experimental progress. Recently, individual experimental parameters (e.g., specific chemical precursors or specific minerals) have been increasingly scrutinized for early Earth plausibility. However, it is rarely the case that the overall system conditions tested for prebiotic potential include multiple co-varying environmental parameters for a single early Earth environment or associations of early Earth environments. This is in large part due to an insufficient understanding of early Earth environmental conditions in specific geologic settings throughout the Hadean. The global constraints that do exist for Hadean conditions are not directly translatable to specific environments or parameters with the overlapping timing of key global parameters (e.g., onset of plate tectonics, decrease of atmospheric CO_2, etc.). Furthermore, the subsequent impact of which environments and conditions were contemporaneously available have yet to be explored, although an attempt has been made to extrapolate this information from early Archean environments (Westall et al. 2018). Within the context of life's origins and the requirements of prebiotic chemistry that might be tested on other planetary bodies and moons, the temporal and spatial scales of what we need and what we can look for are even more disparate.

> **Finding:** Considering the coevolution of early Earth environments in the context of multiple parameters (e.g., temperature, pressure, and pH) and over a range of spatial and temporal scales advances the integration of prebiotic chemistry and origins of life research.

Moving from the Question "Where Did Life Emerge?" to "Where Could Life Emerge?"

Constraining the specific location for the emergence of life on early Earth is a robust area of investigation and is still hotly debated. However, investigations of Earth's potential prebiotic chemistry have highlighted the overall global planetary conditions and specific types of environments that might prove to be viable targets for the rise of life elsewhere. Smith and Morowitz (2016) suggest that the chemical potential of planetary-scale disequilibrium on Earth is focused "to an extreme degree on the rock/water interface and in the mixing chemistry of fluids and volatiles in and near the crust," rendering these environments the most likely for life's origins—an insight particularly pertinent for astrobiological exploration of ocean worlds (ROW 2017). However, it is still widely debated whether the emergence of Earth's life required a strictly surface environment in direct contact with the atmosphere and incoming ultraviolet radiation, or if a subsurface hydrothermal system might have provided the disequilibria necessary for life's origins. What is clear is that while planetary-scale disequilibrium might be the driving force for life's emergence, it is the local-scale manifestations of disequilibrium that determine the outcomes for prebiotic synthesis and life's coevolution with a planet. Both planetary-scale and local-scale disequilibria are important for prebiotic synthesis and life's coevolution with the planet, therefore, consideration of both planetary-scale habitability and localized environments are important in designing successful strategies for searching for life beyond Earth.

What is known of the necessary planetary conditions for the emergence of life on early Earth is applicable to the search for life, if any, on other worlds. For the ocean worlds of the outer solar system, integrating the entire system into the discussion of habitability and the search for life allows the exploration of these worlds to be prioritized and planned. Over the past 20 years, the sophistication of understanding of these systems has grown dramatically. Knowledge of the system as a whole shifts focus from the search for water to the search for many parameters that are needed to support life, such as chemical energy and geologic activity. For example, surface ages are different between these bodies, implying different levels of present day activity that span from vigorous resurfacing in the case of Europa (e.g., Pappalardo et al. 1998; Kattenhorn and Procter 2014; Schmidt et al. 2011; Collins and Nimmo 2009) to relative quiescence in the case of Callisto (e.g., Greeley et al. 2000), despite the fact that many of these bodies have oceans. Based on understanding of terrestrial processes, geologic activity of any type—including, but not limited to, plate tectonics, resurfacing, geothermal activity, or fluid circulation—is part of the formula for habitability. Additionally, while the timing of the origin of life on Earth is not known, presumably there was a characteristic time when a balance of environmental stability and chemical and thermodynamic disequilibria was needed for life to begin. This perspective allows consideration of if and when such a system may have existed on the ocean worlds. A comprehensive understanding of the interplay of chemistry, geology, planetary structure, endogenic, and exogenic energy sources is required to understand how these worlds could operate as systems.

> **Finding:** Planetary conditions that may be habitable today or in the past are not necessarily the same as those that could have fostered the emergence of life. Both are important for the search for life.
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> **Finding:** Due to the complexity of interactions between physical, chemical, and biological parameters and processes, habitability is not a binary property but is best thought of as a continuum of degrees of habitability.
>
> **Finding:** Dynamic habitability and the coevolution of planets and life provides a powerful foundation upon which to integrate diverse astrobiology communities focusing on Earth, the solar system, stellar astronomy, and exoplanetary systems.
>
> **Recommendation: NASA and other relevant agencies should catalyze research focused on emerging systems-level thinking about dynamic habitability and the coevolution of planets and life, with a focus on problems and not disciplines—that is, by using and expanding successful programmatic mechanisms that foster interdisciplinary and cross-divisional collaboration.**

EXAMPLES OF RECENT ADVANCES IN UNDERSTANDING OF DYNAMIC HABITABILITY

The definition of habitability is an environment's ability, or inability, to support life, which can be misinterpreted as a simple yes/no proposition. Recent advances in dynamic habitability have blurred this black-and-white definition. First, dynamic habitability encompasses the transition of an environment from abiotic or prebiotic to biotic, or from biotic to abiotic (e.g., due to a catastrophic event such as large impact or stellar flares). Second, dynamic habitability addresses the spatial and temporal intersections of habitable environments with uninhabitable ones. Increasingly, astrobiologists have scrutinized these intersections by studying life living in extreme and often isolated environments on Earth. As in the case of *refugia*, such environments occur against the backdrop of conditions largely considered uninhabitable, and the isolated communities inhabiting these specialized *niches* demonstrate how habitability can be a local phenomenon in both space and time. In other cases, the extreme conditions are more generalizable to surface conditions but push the boundaries of conditions understood as being "habitable."

Another area of significant advance in dynamic habitability has been the discovery of a previously unknown subsurface biome. While planetary surfaces receive abundant energy from the light of their host star, they are also subject to potentially sterilizing events such as giant impacts and stellar flares. Subsurface environments are potentially protected from such disruptive events. On Earth's surface, sunlight drives photosynthetic ecosystems—those based upon the products of photosynthesis. In the

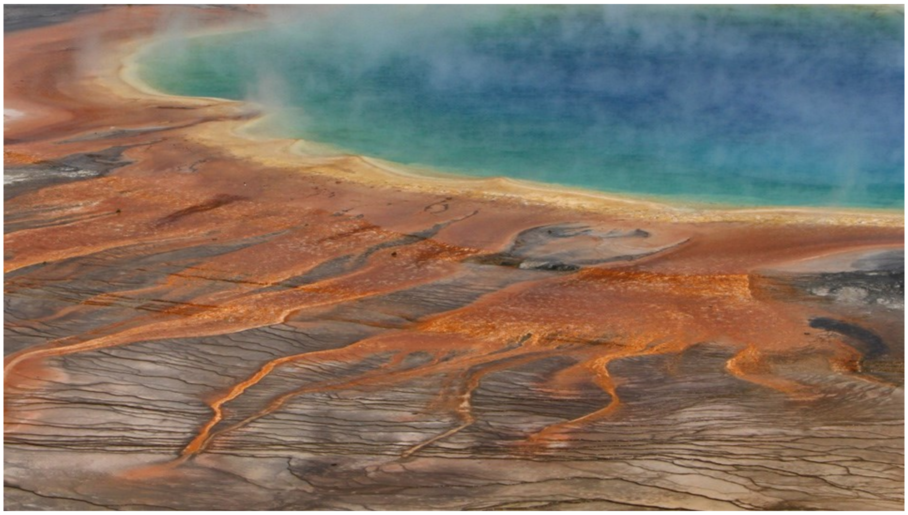

FIGURE 2.1 Hotspring environment in Yellowstone National Park. SOURCE: https://www.nps.gov/yell/learn/nature/hydrothermal-systems.htm; courtesy NPS/Jim Peaco.

subsurface, however, biological communities are increasingly found to exist beyond the direct influence of sunlight and can be entirely sustained by chemical energy—chemosynthetic communities. Examples of such communities include life in the deep Earth, in subsurface aquifers, caves, and life at and below the seafloor. Although many such organisms may have been common on early Earth (Westall et al. 2015a,b), as many of these subsurface ecosystems are explored for the first time on the modern Earth, their expressions at the surface and in the atmosphere remain unknown. Efforts to consider their impact are tied to a better understanding of the thermodynamic drivers of the ecosystems—whether abundant energy is available or not, and if the life exhibits vigorous, slow, or even dormant metabolic processes. With increasing interest in extreme surface and subsurface environments on other planets, understanding the role of these systems and their impact on planetary evolution and life detection is critical, making them a frontier of astrobiological research for which a number of notable examples are provided here.

Refugia and Ephemeral Habitats

Biological ecosystems develop to thrive in specific niches. Given the generally clement conditions of Earth’s surface today, it is common to think of niches as spatially large and connected and temporally long-lived. This need not be the case universally. Microbial life in the Atacama Desert of Chile provides a case in point. In the hyperarid core of the desert, photosynthesizing microbial communities exist on the undersides of translucent rocks. The rocks provide protection from desiccation and solar ultraviolet radiation while their translucence allows the microbes to access sufficient light for photosynthesis. These communities are rare and occur in small, isolated islands surrounded by microbially-poor soil (Warren-Rhodes et al. 2006). Similarly, endolithic communities are found sparsely distributed throughout terrestrial hot spring systems (e.g., Rogers et al. 2014; Hynek et al. 2011; Walker et al. 2005) (Figure 2.1). Such examples highlight how finding microbial life in habitable, albeit extreme, environments requires an understanding of environmental controls and their interactions with biologic processes integrated over space.

These Earth examples increase the range of possible niches in which to search for signs of extinct or extant life on the surface of Mars. The search becomes not only for habitats that may have become inhabited as or after life emerged, but also for locations where life or signs of extinct life may persist despite widespread loss of surface habitability. Current understanding of the martian surface during the pre-Noachian and early Noachian (see Box 2.3) suggests that life could have emerged on the planet (McKay 2010; Westall 2015). Life could not have emerged everywhere, however, and the locations that

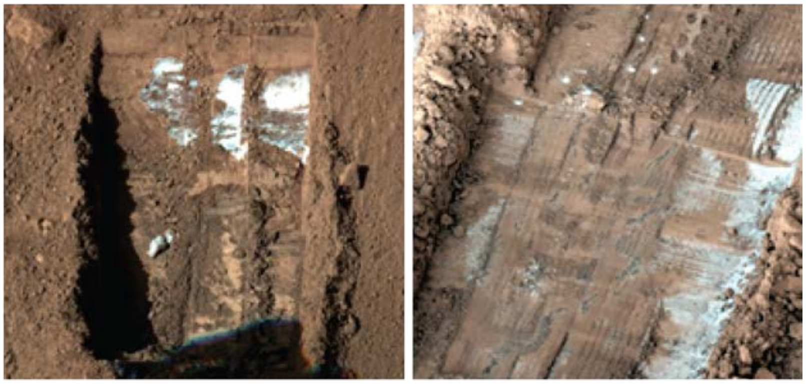

FIGURE 2.2 Ice and frost observed at high northern latitudes on Mars. (Left) Ice revealed in a shallow trench dug by the Phoenix lander. (Right) Frost observed on the trench dug by the lander. SOURCE: After Renno et al. (2009).

would have had the right conditions for hosting the emergence of life would have been isolated both in space and time (Westall et al. 2015a). Furthermore, life it seems could not emerge there today in any known surface environment. There exists the possibility, however, that viable cells on Mars could survive and maybe flourish for short periods in isolated, transient habitable *niches* at the surface (Rettberg et al. 2016). In addition to developing the hypothesis that it is not necessary for the entirety of the surface of an extraterrestrial body to be habitable for the emergence or persistence of life, this example demonstrates that integration of environmental controls and their interactions with biological processes is one that occurs over not just space, but time as well.

The view of an ancient Mars surface dotted by habitable surface environments such as lakes and playas (Ehlmann et al. 2008; Squyres et al. 2004; Grotzinger et al. 2005; Wray et al. 2011; Michalski et al. 2013), and aquifers and hydrothermal systems (Skok et al. 2010; Ehlmann et al. 2011; Saper and Mustard 2013) has been enhanced by results from landed missions to Mars including Viking, Mars Pathfinder, Phoenix, the Mars Exploration Rovers, and Mars Science Laboratory, as well as the orbital missions Mars Global Surveyor, Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter and Mars Atmosphere and Volatile Evolution mission (MAVEN) (Arvidson 2016). Recently, findings of the ongoing Mars Science Laboratory mission have documented the potential for ancient Gale Crater sediments to provide nutrients and energy for life (Grotzinger et al. 2014); combined with the presence of water, the crater could have served as an ephemeral habitat for life. Since publication of the 2015 Astrobiology Strategy, however, attention has been turning increasingly to the idea of the modern martian surface as one existing on the edge of habitability (Ehlmann 2018). The identification of ephemeral martian surface habitats—existing from days, as in the case of the isolated environments above, to hundreds of thousands of years—is an area of increasing interest.

This interest has been driven in part by a rapidly-evolving understanding of the martian cryosphere. Radar sounding of the south polar ice deposits has revealed volumes of carbon dioxide ice that, if released as a gas, could double its atmospheric pressure (Phillips et al. 2011; Bierson et al. 2016). This would bring more of the martian surface above the triple point of water (Ehlmann 2018). Bierson et al. (2016) hypothesize that this has occurred as recently as within the last 1 Myr, possibly even multiple times. At the same time, the inventory of near-surface water ice reservoirs—including, but not limited to, pore-filling ice in the regolith (Boynton et al. 2002; Pathare et al. 2018), mid-latitude glaciers (Holt et al. 2008), and contiguous sheets of mid-latitude ice (Dundas et al. 2018)—is large (Carr and Head 2015) and increasing (Dundas et al. 2018; Pathare et al. 2018) (Figure 2.2). In concert with the possibility of periodic increases in atmospheric pressure, the extensive nature of near-surface water ice deposits raise the potential for formation of ephemeral surface water, thereby increasing chances for habitability on timescales of obliquity changes (Ehlmann 2018).

Over the past 15 years, discoveries from both spacecraft in orbit and landed on Mars have sparked a major revision in our thinking about the nature of diagenetic fluids and subsurface groundwater on the planet and their role in habitability over time (Ehlmann and Edwards 2014; Ehlmann et al. 2016, Grotzinger et al. 2015; Goudge et al. 2015). The recent report of strong seasonal variation in background levels of methane in the Mars atmosphere, and the resultant renewed investigation of sources(s) for that methane, underscores the necessity to consider both surface and subsurface processes (Webster et al. 2018, 2015). Extending the lessons learned from terrestrial analogs about subsurface habitability, fluid history and water-rock reaction, rock-hosted life, and preservation to other space exploration targets such as Mars is valuable even while recognizing the challenges of accessing non-terran subsurface systems.

Permission Pending

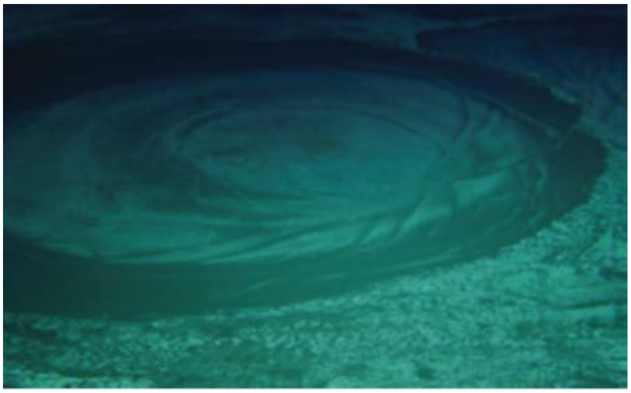

FIGURE 2.3 Brine habitats are found around the world in the surface and subsurface. (Left) Antarctica's Blood Falls. (Right) Brine pool on a deep-sea mud volcano in the Mediterranean. Microorganisms that thrive in saline fluids and brines are found at both sites. SOURCE: After Boetius and Joye (2009). Right image reproduced with permission © Ocean Exploration Trust/Nautilus Live.

Saline and Hypersaline Environments

The martian example above alludes to the possibility of forming water through melting when atmospheric pressure is raised. Investigations on Earth and Mars, however, demonstrate that other means may exist for forming ephemerally habitable aqueous environments. For example, salts increase the range of environmental conditions under which liquid water may exist (Fischer et al. 2014). Salts have the following three impacts on liquid water that are pertinent when considering the possibility of life on other planets (Haberle et al. 2001; Chevrier et al. 2009; Renno et al. 2009; Gough et al. 2011; Fischer et al. 2016):

1. They lower the freezing temperature of water, allowing it to remain in a liquid state at temperatures below 0°C;
2. They decrease the partial pressure of water vapor, in equilibrium with aqueous solutions, lowering evaporation rates in tenuous dry atmospheres; and
3. They form crusts on the surfaces of liquids, which further inhibit evaporations.

These three effects increase the range of conditions in which brines can be stable.

On Earth, a diverse array of terrestrial microorganisms thrives in the hypersaline habitats created by brines (Boetius and Joye 2009). These environments (e.g., Figure 2.3) include subsurface saline aquifers, deep-sea brine pools, ancient subglacial brine reservoirs (Green and Lyons 2009; Mikucki et al. 2009; Joye and Samarkin 2009; Biddanda et al. 2009; Thomas and Dieckmann 2002), and surface bodies of water, like the Dead Sea (Arahal et al. 1996). Examining the communities in these environments expands the known limits of life. For instance, the discovery of sulfur- and iron-cycling microbial communities in the subglacial brine that episodically drains from Taylor Glacier in Antarctica's Dry Valleys (Mikucki et al. 2009) is particularly relevant to understanding habitability on other worlds. The cycling of sulfur, methane, and iron in hypersaline habitats in the absence of sunlight underscores the metabolic flexibility of extremophiles (e.g., Boetius and Joye 2009; Li et al. 2016; Magnabosco et al. 2018). Microbes thriving in similar brine channels and brine inclusions in sea ice, which concentrates nutrients and organics, making them readily available for microbial consumption (Junge et al. 2001), also may apply to ocean world environments. In cold worlds like Europa, tidal heating could cause the formation of regions that could produce liquid brines and preserve them in cracks and crevasses like those found in terrestrial sea ice (Junge et al. 2001). If such regions exist in the subsurface of Europa and other icy worlds, they may be potentially habitable.

In another example of microbe resiliency and persistence in hypersaline environments, halophilic archaea isolated from Dead Sea samples more than 50 years after their collection (Arahal et al. 1996) indicate low mortality rates in briny environment (even up to 20% salt content; Boetius and Joye 2009). Notably, similar halophilic organisms are found in many branches of the tree of life, including archaea and bacteria. This suggests that either adaptation to saline environments occurred numerous times, or that lateral gene transfer occurred during their evolution.

On Mars salts capable of forming aqueous solutions at martian temperatures, such as perchlorates of calcium, magnesium, and sodium, were discovered in the polar and equatorial regions (e.g., Hecht et al. 2009; Glavin et al. 2013; Ming et al. 2014; Martin-Torres et al. 2015). Such perchlorates may be responsible for the formation of ephemeral brine on the surface of Mars (e.g., Renno et al. 2009; McEwen et al. 2011, 2013; Ojha et al. 2015). One proposed manifestation of modern brines on the surface are recurring slope lineae (RSL)—annually occurring, narrow lineae of darker albedo than underlying material that occur on steep slopes and lengthen through the warm season (McEwen et al. 2011). By what process RSL form, however, is still ambiguous, as they may also form by dry granular flow (Stillman and Grimm 2018). However, if RSL are formed by brines, they are of interest because they could ephemerally host microbial cells (Rettberg et al. 2016). Moreover, RSL may point to more stable environments in the subsurface.

Continental Subsurface

Deep marine, chemosynthetic life has long been of interest. Investigations of such communities are now expanding to include subsurface continental settings (Suzuki et al. 2017; Kietavainen et al. 2017; Magnabosco et al. 2018). Studies in Precambrian cratons have transformed our understanding of the habitability of Earth's subsurface in fracture water located deep within crystalline rocks that are billions of years old. Precambrian (and specifically Archean) settings have been the focus of many analog studies for Mars. Deep groundwaters in rocks of more than 3 billion years in age reveal preservation of fluids with residence times ranging from millions to billions of years (Lippmann-Pipke et al. 2011; Holland et al. 2013; Warr et al. 2018). Serpentinization relates oxidation of FeO in the crust to H_2 production (Sleep and Bird 2007). Other moderate- to low-temperature processes of water-rock reaction producing hydrogen-, methane-, and sulphate-rich fracture fluids include radiolysis (Lin et al. 2005a,b; Li et al. 2016) and a range of other hydration reactions acting on mafic and ultramafic minerals (Sherwood Lollar et al. 2014; Mayhew et al. 2013). Such processes have also been invoked in the context of understanding production of methane on Mars (Webster et al. 2018; Atreya et al. 2007; Chassefiere et al. 2016) and the role of water-rock interactions in potential habitability of ocean worlds and icy bodies such as Europa and Enceladus (Bouquet et al. 2017; Hand et al. 2016; Waite et al. 2017).

Expanded understanding of subsurface habitability on Earth has implications for the search for life on Mars, where ionizing radiation and oxidation of the upper 1.5 to 3 m pose two great challenges to the existence of life on the surface (Eigenbrode 2018). Speculation about potential habitability arising from subsurface water at depth (Ehlmann 2018) or life in shielded lava tubes or caves (Leveille and Datta 2010; Blank et al. 2018) has motivated the search for life in the subsurface of that planet. To this end, the

Roscosmos and European Space Agency joint ExoMars 2020 rover, whose goal is to search for signs of past or present life, will carry a drill able to reach 2 m below the surface of the planet. Samples taken from depth will be retrieved and analyzed for signs of organics or possible visible biosignatures using the rover's instrument suite (Vago 2018). The NASA Mars 2020 rover will also carry a drill for the recovery of shallow (i.e., to a depth of approximately 5 cm) subsurface samples, however, those samples will be cached on the surface for return to Earth at an unspecified time in the future (Ehlmann 2018). The sites to be sampled will be identified using instruments on the rover, but detailed studies will be done once the samples have returned to Earth.

Full consideration of in situ astrobiological analyses and future missions targeting the shallow subsurface of Mars is absent in the NASA portfolio and needs considerable development in the upcoming decade. Shallow planetary subsurfaces are easily accessible and extremely interesting as a possible microbial habitat when they are wet. They are shielded from radiation, and mixing by a variety of surface processes that impact the shallow subsurface could provide the nutrients necessary for sustaining microbial life. On Mars, aeolian abrasion is one of the most important, currently active, weathering processes. Chemical reactions induced by aeolian process could also have important implications for life and habitability (e.g., Atreya et al. 2006; Kok and Renno 2009).

The growth of salt crystals in ice cracks and rock pores is another important weathering process. There is also evidence that this process is currently active on Mars. Salts have the potential of creating pockets of wet brines in the shallow subsurface of Mars (Fisher et al. 2014, 2016). Comprehensive measurements of regolith wetness and the possible detection of brines could elucidate habitability and aqueous weathering processes not only on Mars, but also on other potentially habitable worlds. Measurements of dry weathering processes, such as abrasion by moving sand grains, could elucidate the supply of nutrients necessary for sustaining microbial life in shallow planetary subsurfaces. Small, power-efficient instruments for studying aeolian processes, weathering, and regolith wetness will be useful for enabling the collection and analysis of samples of the most astrobiologically relevant areas.

Marine Subsurface and Ocean Worlds

Deep submarine oases, such as hydrothermal vents (Figure 2.4), highlight the potential for extensive ecosystems in highly dynamic tectonic settings. Active microbial communities, however, have also been found throughout the more widespread and less dynamic crystalline and sedimented oceanic crust (Edwards et al. 2012; Kallmeyer et al. 2012; Colwell and D'Hondt 2013). These microbial communities are both chemosynthetic and photosynthetic-based, are supported by a variety of energy and carbon sources, and proliferate over a broad range of temperature, salinity, pH, and redox conditions. Yet fundamental questions remain unanswered: How much of the total planetary biomass is represented by these subsurface communities? What are the mechanisms for prokaryotic life's dispersal and transport? How do biodiversity and total biomass vary with depth below surface? and What role do the combined effects of temperature, pH, redox conditions, and pressure play in microbial adaptation and survivability?

The isolation of several high-pressure, or piezophilic, microbial strains as well as recent experiments showing that decompression of piezophiles causes cell death, underscore the need to include the effects of pressure when considering habitability and life detection. On Earth, piezophiles have been isolated from deep terrestrial boreholes and mines, deep ocean basins, and deep sea hydrothermal vents (Abe and Horikoshi 2001). Studies to understand the high-pressure biosphere have pushed the boundaries for high-pressure growth to 140 MPa (Kusube et al. 2017) and high-pressure survival up to 2 GPa (Sharma et al. 2002; Vanlint et al. 2011). Furthermore, growth at elevated pressures has also extended the known high temperature limit of life (Takai et al. 2008) to 122°C, as well as the high temperature limit of several individual species of hyperthermophiles (Zeng et al. 2009). The link between high-pressure and high-temperature organisms exemplifies the criticality of evaluating habitability through the lens of interconnected environmental parameters. In addition to fundamental questions about the nature and activity of life in the marine subsurface, recent research is advancing the frontiers of understanding of procedural best practices—for example, optimizing sensitivity of life detection and characterization in the context of challenges of contamination, related to both sample retrieval and sample handling (Sheik et al. 2018).

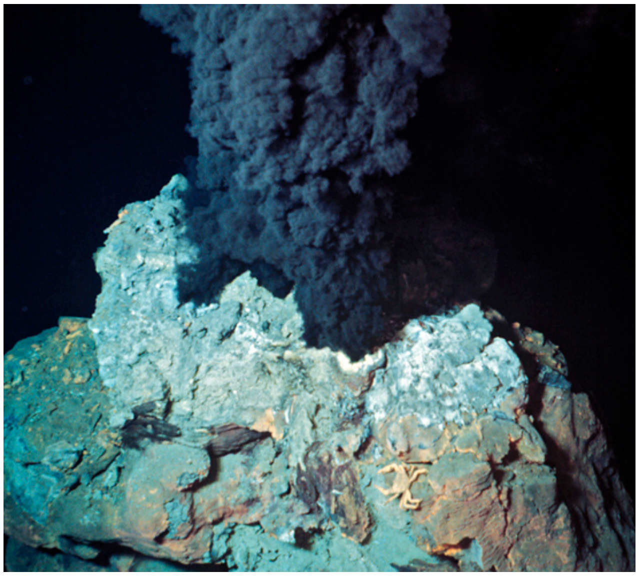

FIGURE 2.4 Submarine hydrothermal vent ("black smoker"). SOURCE: http://www.whoi.edu/page.do?pid=83497&tid=4102&cid=57933&i=4; © Woods Hole Oceanographic Institution.

As understanding of extreme marine life on Earth is advancing, so too is the discovery that oceans in the outer solar system are relatively common (Khurana et al. 1998; Kivelson et al. 2000; Husmann et al. 2006; Thomas et al. 2007; Iess et al. 2012; Iess et al. 2014; Keane et al. 2016). For many of these worlds, the most likely habitats are below the surface. On Europa (Figure 2.5), energy for metabolic processes at the seafloor could derive from tidal activity, radiogenic heating, and ongoing serpentinization that both releases energy and could cause fractures to allow active seafloor alteration (Vance et al. 2016; Sherwood Lollar et al. 2014). Additional habitats within Europa's ice shell may also exist. These range from veins along grain boundaries, as seen in glacial and accretion ice on Earth (Priscu and Christener 2004), to small distributed brine zones from partial melting (Collins et al. 2000; Pappalardo and Barr 2004), to larger subsurface melt pockets induced by tidal convection or diapirism, or eutectic melting (Showman and Han 2004; Sotin and Tobie 2004; Schmidt et al. 2011). Icy habitats may be linked to sub-ice ocean processes or carry with them a record of ocean conditions (Vance and Goodman 2009; Soderlund et al. 2014). Recent, but indirect, reported detections of plume activity at Europa (Sparks et al. 2016, 2017) are consistent with the release of water vapor by a process that does not necessarily depend upon tidal forcing (Roth et al. 2014a,b), which is insufficient to fracture Europa's ice shell (Goldreich and Mitchell 2010). Therefore, it is possible that these plumes originate from within the ice shell rather than the ocean (Walker and Schmidt 2015). This suggests that understanding the interactions between surface, oceans, and the underlying subsurface are likely critical for understanding astrobiological implications (ROW 2017).

Enceladus, too, likely possesses a subsurface ocean (Iess et al. 2014) that is released by a south-polar plume consisting of many individual jets (Porco et al. 2006; Spencer et al. 2006). Enceladus has likely become active in the recent geologic past (Meyer and Wisdom 2007), and its activity may be punctuated (Nimmo and Pappalardo 2006; Meyer and Wisdom 2008; O'Neill and Nimmo 2010). Although Cassini data do not clearly articulate other regions of present day activity, the interpreted presence of crater relaxation (Bland et al. 2012) and thermal-infrared measurements by Cassini suggest high heat flow.The ice shell, ocean, and seafloor may all provide habitable environments, particularly given observations of plume chemistry that indicates hydrothermal activity and the production of hydrogen, which can serve as an electron donor for both energy transduction and the reduction of carbon dioxide for biosynthesis (Waite et al. 2006; Postberg et al. 2011; Hsu et al. 2015; Glein et al. 2015; Waite et al. 2017). Further, seafloor serpentinization (Hsu et al. 2015) may make life possible through the production of chemical energy in the form of methane and molecular hydrogen (Waite et al. 2017).

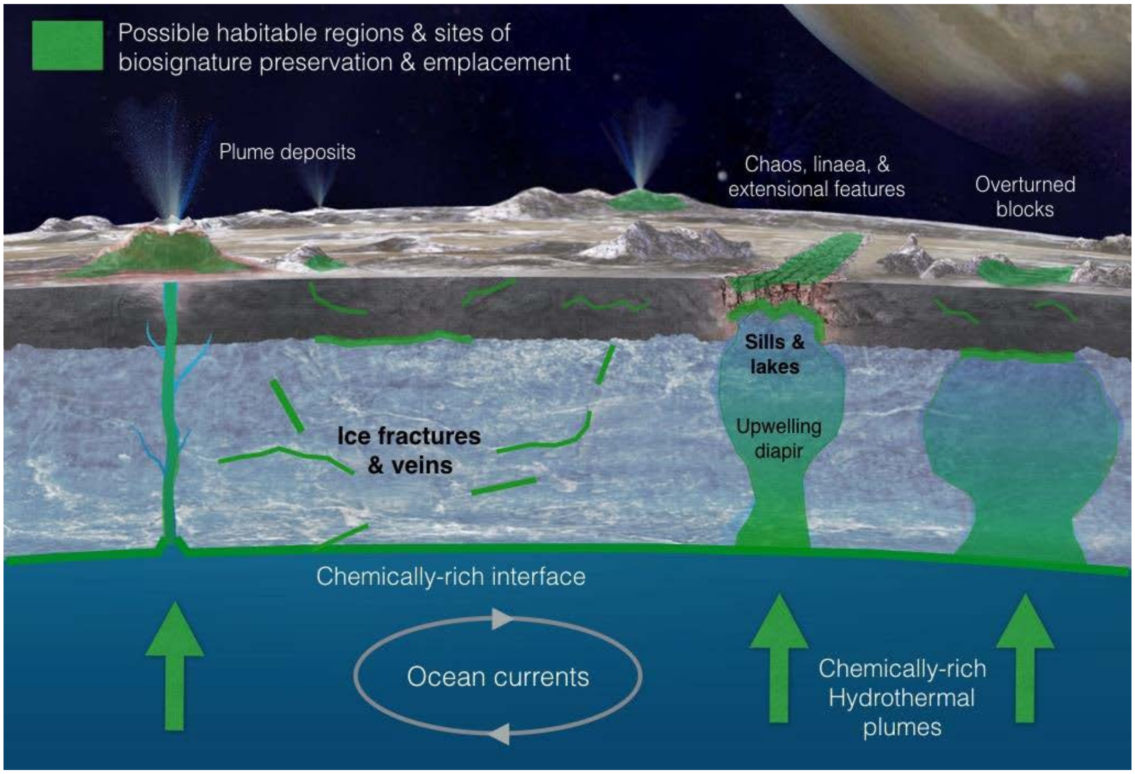

FIGURE 2.5 Europan environments that may harbor life or preserve biosignature. A variety of geologic and geophysical processes, including ocean currents governed by tides, rotation, and heat exchange, are required to drive water from the subsurface to the surface and govern how any exchange operates. SOURCE: Kevin Hand, Jet Propulsion Laboratory, "On the Habitability of Ocean Worlds," presentation to the Workshop on Searching for Life across Space and Time, December 5, 2016.

The plumes emanating from Enceladus, and potentially Europa, provide evidence of relatively intense cryoactivity reshaping their icy crusts, and modelling suggesting subsurface oceans have led to increased interest in the potential habitability of these two moons. Metabolisms fuelled by natural radiogenic energy (i.e., radiolysis of water at the rock-water interface as used by sulphate-reducing bacteria deep in the Earth's crust; see Lin et al. 2006; Onstott 2016; Li et al. 2016) could occur on icy bodies. Further, the detection of hydrogen and methane—which indicate ongoing hydrothermal rock-water interactions like those favoured in scenarios of the emergence of terran life—and formaldehyde suggest prebiotic conditions in Enceladus' oceans (Waite et al. 2017). In light of these discoveries, there is debate as to whether remote plume characterization to detect biosignatures that consider molecular composition, organic complexity, and Gibbs free energy is sufficient for life detection, or if obtaining a plume sample in a fly-by for on-board analysis and/or sample return is mandatory (see Chapter 6).

Titan's surface reservoirs of liquid hydrocarbon are of interest to the astrobiology community (see Box 3.1), but the moon also harbors a deep subsurface global ocean (Iess et al. 2012). While

Ganymede and Callisto also have subsurface global oceans, the extreme thickness of these moons' ice shells impedes interactions between the surface and subsurface, which has its own implications for habitability. At Titan and Ganymede, dense, high-pressure ice layers may separate their oceans from their silicate mantles, which could inhibit water-rock reactions, such as serpentinization, postulated to be sources of chemical energy for life. Knowledge of serpentinizing systems on Earth is driving interest in the seafloor interactions on ocean worlds. Measurements of the properties of these oceans, while challenging to make, have begun a discussion about how to interpret chemical signatures of water-rock reactions. It is unclear whether Europa's ocean pH (Glein et al., 2015, suggested a pH of 11 or 12) would foster habitability or indicates serpentinization gone to completion, fully reducing Europa's ocean. Small silica particles observed in Enceladus' plume (Hsu et al. 2015) were interpreted as evidence of habitability through ongoing hydrothermal activity, and the detection of molecular hydrogen would seem to reinforce this assumption, because products available for microbial metabolisms exist (Waite et al. 2017). While the very presence of this hydrogen may suggest it is not actively being consumed, the discovery of extant microbial communities of hydrogen-utilizing, sulfate-reducing bacteria in the Earth's subsurface, where ambient hydrogen concentrations are at the millimolar level, underscores the need to consider the effects of relative rates of production and storage of electron donors and acceptors (controlled by porosity and permeability as well as the rate of water-rock reaction), versus the potentially slow rate of metabolic consumption in subsurface environments (Lin et al. 2006; Hoehler and Jorgenson 2013; Sherwood Lollar et al. 2014; Li et al. 2016).

> **Finding:** Expanded understanding of habitability of chemosynthetic subsurface environments, brine stability, and adaptations of life to saline fluids have widespread implications for the search for life in the solar system.

Fast versus Slow Life

From the examples given above, it is clear that there are a range of potential environments for life, from the austere to those having rich natural resources and diverse local conditions. These environments provide a corresponding range of opportunities for life's emergence, differentiation, and dispersal. The more complex environments provide the greatest opportunity for life but also give rise to more complex abiotic processes that raise background complexity and challenge-life detection studies. There is a gradient for both the richness of potential signatures of life and the degree of potentially obfuscating non-biological processes, and it is not clear where on that gradient the best opportunities for life detection are located.

Further confounding the search for life is the interplay between metabolic rates and background processes. As previously mentioned, identifying signatures of so-called "fast life" existing in energy-rich environments may prove to be more or less challenging than finding "slow life" in energy-starved environments. The example from Enceladus highlights this conundrum, where hydrogen may be present either because it is not being actively consumed or because its rate of production exceeds that of slow metabolic consumption. Increasingly, research into slow, and even dormant, life on Earth opens the possibility of discovering such entities on other worlds.

Another example of slow-growing cells to take into account when considering planetary habitability are those entities residing in the Earth's crust or deep sediments. Deep-sea sediments host viable cells down to depths of nearly 2 km (Ciobanu et al. 2014; Jorgenson and Marshall 2016). In oligotrophic environments, the low availability of both nutrients and water severely limits cell viability. Cells in this environment have a remarkably slow metabolic turnover of about one cell division per thousand years (Ciobanu et al. 2014; Braun et al. 2017). The fractured crust is a somewhat different environment, where water that has infiltrated deep fractures can entrain microbes over long periods of time at depths up to 3 to4 km (Onstott 2016). Each fracture system, some as small as 1 cm, is an oasis for life (Sleep and Zoback 2008; Sherwood Lollar et al. 2007), and the microbial biomass in these subsurface habitats is low compared to that at the surface. Autotrophy and methane cycling are the main means of metabolic support for these deep microorganisms, with cell turnover times that range from one to hundreds of years (Onstott 2016).

> **Finding:** "Slow" life that is barely able to survive in an austere environment may be detectable because the noise level is low, whereas "fast" life in a rich environment may be detectable because the signal is high. Assessing the relative signal-to-noise ratio of each type of population in its given environmental context would help identify corresponding biosignatures that are most relevant and distinctive.
>
> **Recommendation: NASA's programs and missions should reflect a dedicated focus on research and exploration of subsurface habitability in light of recent advances demonstrating the breadth and diversity of life in Earth's subsurface, the history and nature of subsurface fluids on Mars, and potential habitats for life on ocean worlds.**

BOX 2.3
Martian Geological Periods

The geological histories of both Earth and Mars are divided into four distinct eons and periods, respectively. On Earth, eons are distinguished from one another based on the stages of life they hosted—for example, the Hadean eon being devoid of life and the Archean eon corresponding to the emergence of life. On Mars, the absence of fossil evidence precludes such divisions. However, the layering of geological features—for example, an impact crater on top of a lava flow—dates these features relative to one another and uncovers aspects of the martian history. A comparisons between Mars's periods and Earth's eons is given in Figure 2.3.1. Each martian period is named for a set of surface features which define it, from most recent to oldest as follows:

1. *The plains and volcanic materials of the Amazonis Planitia*. The Amazonian period, lasting from ~3.0 billion years ago to the present day, is characterized by low impact rates and hyperarid conditions.
2. *The ridged plains of the Hesperia Planum*. The Hesperian period, lasting from ~3.7 to ~3.0 billion years ago, is characterized by catastrophic flooding that created outflow channels across the martian surface.
3. *The Noachis Terra in the southern highlands*. The Noachian period, lasting from ~4.1 to ~3.7 billion years ago, is characterized by widespread cratering and the resulting formation of impact basins. This period also shows evidence of major volcanic episodes.
4. All of martian history prior to ~4.1 billion years ago is known as the pre-Noachian period. Most features from this period have been erased over time, so little is known about it. However, the pre-Noachian period corresponds to the time in Mars' history when it may have been most Earth-like. This period had the highest likelihood of harboring life, so it remains a critical piece of understanding Mars' potential for habitability.

The uncertainty in the beginning and ending boundaries between these periods remains high, and estimates on these ranges continue to improve as the quality of data improves. It is likely that major advances in defining martian chronology will necessitate at least one sample return mission.

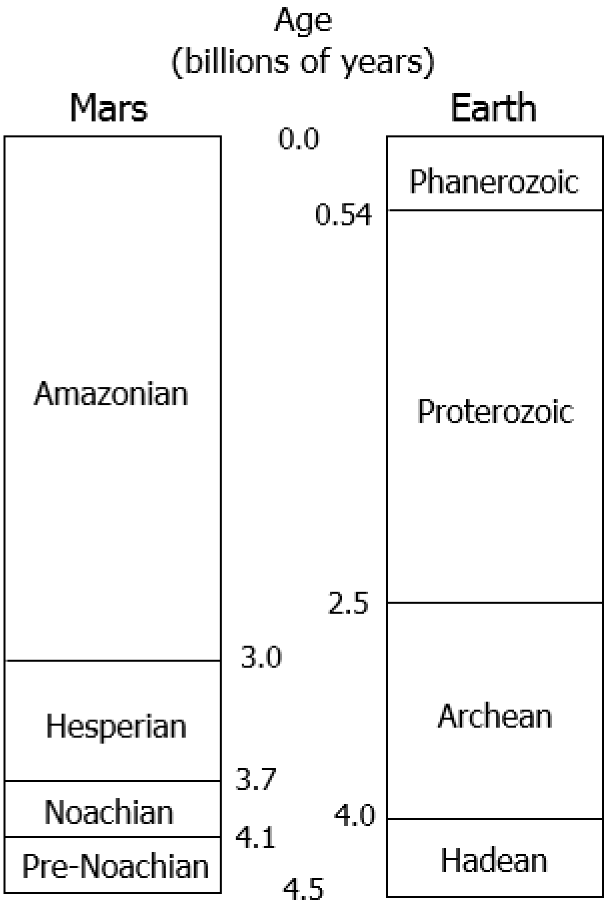

FIGURE 2.3.1 Major events in the geological histories of Earth and Mars over the last 4.5 billion years. The timing of the boundaries between Mars's three major named geological periods is highly uncertain because of the absence of an absolute calibration of the ages of martian surface features. Moreover, the geological record of the earliest events in martian history, those of the so-called pre-Noachian era, has been largely erased by subsequent events, including the heavy bombardment that took place during the Noachian era. SOURCE: Adapted from National Research Council, 2007, *An Astrobiology Strategy for the Exploration of Mars*, The National Aademies Press, Washington, D.C.

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3

Comparative Planetology and Multi-Parameter Habitability Assessment

Since publication of the 2015 Astrobiology Strategy (NASA 2015), there has been significant progress in characterizing the extreme range of habitable environments on Earth and identifying potentially habitable environments elsewhere in the solar system and beyond. Habitable environments on Earth, each characterized by a specific set of processes and parameters, remain a touchstone in understanding habitability requirements. The study of the examples posed by habitable Earth ecosystems and improved understanding of the current chief astrobiological targets within the solar system—Mars, Europa, Enceladus, and Titan—have illuminated the importance of understanding these worlds as integrated systems when assessing their potential habitability. Further, the post-2015 discovery of Earth-sized planets orbiting M-dwarf stars in their habitable zones—a term that has, at times, been used to mean different things in different communities (see below)—has transformed the field of exoplanet studies from a statistical exercise predicting that such planets are common, to providing specific targets amenable to near-term telescopic study.

These advances have led to new, holistic approaches for understanding habitability. Foremost of these is the concept of habitability systems (Figure 3.1). In habitability systems thinking, the roles processes play in a system to facilitate or catalyze conditions that support life, as well as the interactions and feedbacks between these processes, supersede the specifics of any given planetary environment. For example, on Earth, plate tectonics sustain a planetary disequilibrium that generates thermal and geochemical gradients. On an ocean world, tidal heating, radiogenic heating, or interactions between circulating water and rock could play the same role.

In a similar vein, the community has begun a reevaluation of the term *habitable zone*. Traditionally, the habitable zone has been defined as the range of distances from a parent star in which an Earth-like exoplanet could potentially maintain water on its surface (Kasting et al. 1993; Kopparapu et al. 2013). But there are different ways to estimate this range. One-dimensional (1D) climate models yield a comparatively narrow, or *conservative*, range. Empirical estimates based on observations of Mars and Venus yield a somewhat broader, or *optimistic*, range. The optimistic habitable zone extends considerably closer to the star, which may be appropriate if clouds (which are not explicitly included in 1D climate models) help to keep a planet cool.

More recently, systems thinking has given rise to the concept of habitability indices, which instead combine constraints on multiple parameters and processes, such as the planet’s initial composition or the host star’s evolution. Recent studies demonstrate that evolving interactions between planet, star, and planetary system impact habitability, allowing us to advance beyond the classical concept of habitable zone to provide a more comprehensive assessment of potential habitability when evaluating and ranking targets for biosignature searches. Within the solar system, multiple aspects of the environment and its history are needed for habitability assessment and surface and subsurface site selection. In parallel with the increasingly broad identification of potentially habitable environments that stems from systems-level thinking, there has been a renewed focus on habitability assessment as a multidimensional, probabilistic process that evolves through time—multiparameter habitability assessment.

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FIGURE 3.1 Factors affecting habitability. This diagram lists the properties and processes that may impact a planet’s ability to support a surface ocean of liquid water (denoted by the central circular vignette of waves breaking on a beach), organized by whether these are characteristics of the planet (*lower panel*), its parent star (*upper, left panel*), or its planetary system (*upper*, *right panel*). Factors that can be determined or constrained for a given habitable zone candidate will improve the assessment of potential habitability. Font color denotes properties or processes that could be established directly from data collected with a sufficiently powerful telescopes (blue), those that mostly require modeling for their interpretation, possibly constrained by some observations (green), and those that are accessible primarily through theoretical modeling (orange). SOURCE: Meadows and Barnes (2018).

Strong synergies between solar system studies and exoplanet science are also emerging. For example, within the solar system, perspectives on volatile evolution and delivery can be investigated directly through observations of and missions to small body populations, while planetary system observations demonstrate how planetary system architecture influences small body inventories and volatile and organic delivery as it evolves from debris and protoplanetary disks. Recent discoveries of exo-Venuses—terrestrial-size planets (i.e., <1.6 Earth radii) in an orbit closer to the parent star than the inner edge of the habitable zone—and habitable zone terrestrial planets have also enabled an exciting new era of comparative planetology. Comparative studies of planetary processes and outcomes in the solar system, and the recently revealed characteristics of analog exoplanets, will inform and strengthen understanding of the processes that shape planetary habitability and provide a major new opportunity for interdisciplinary research that integrates multiple research communities.

TERRESTRIAL EXOPLANETS AND THE SEARCH FOR HABITABILITY

Since the release of the 2015 Astrobiology Strategy, exoplanet astrobiology has transformed from a field driven by promising statistical predictions into one with nearby targets accessible to near-term observation. The revolutionary Kepler mission began this transformation with its initial discovery of two promising planets in the habitable zones of their parent stars, Kepler-62f and Kepler-186f (1.4 and 1.1 times the size of Earth, respectively). However, both planets were too distant for follow-up observations to obtain masses that might then be used to confirm their rocky bulk densities and compositions. Instead, their likely terrestrial nature was hypothesized based on their radii being less than the 1.5 Earth radius limit below which a planet is more likely to be rocky (Rogers 2015). With Kepler's final data set now released, observations of hundreds of thousands of distant stars have been used to project that approximately 50 percent of Sun-like stars may host Earth- and super-Earth-sized planets in their conservative habitable zones (Kopparapu et al. 2018, Table 3).

Kepler's data set includes 4,034 planet candidates. Of these, approximately 50 are possibly rocky planets with radii less than 2.0 Earth radii and orbiting in their host star's habitable zone (Figure 3.2). Although Kepler's planets are many hundreds to thousands of parsecs (pc) distant, and therefore too faint for the follow-up observations needed to assess their habitability, a recent flurry of discoveries by ground-based telescopes of relatively nearby (within 20 pc of the Sun) habitable zone planets has provided concrete targets for further study. The first of these was the discovery of Proxima Centauri b, an exoplanet with a minimum mass of 1.3 Earth masses in an 11-day orbit around the closest star to the solar system, Proxima Centauri (1.3 pc; Anglada-Escude et al. 2016). Proxima Centauri is a low-mass (0.12 solar mass), M-dwarf star, and Proxima Centauri b's short orbital period places it squarely within the habitable zone. The second remarkable discovery was that the late M-dwarf star named TRAPPIST-1 (0.080 solar mass) hosts at least seven Earth-sized exoplanets (12 pc; Gillon et al. 2017) that transit, or cross in front of, the star. Three (TRAPPIST-1 e, f, and g) of the seven planets orbit in the habitable zone and are within ~10% of Earth's radius. Transit timing variations were used to determine that the masses of these exoplanets (0.62, 0.68, and 1.34 Earth masses, respectively) and the derived planetary densities suggest that the planets are of comparable composition to Earth, or that they have a larger fraction of interior ices (Grimm et al. 2018). Although more distant than Proxima Centauri b and orbiting a fainter star, the fact that the planets transit their star means that they will be prime targets for spectroscopic observations by the future James Webb Space Telescope (JWST). It is important to note that M-dwarf stars span a wide range of mass and luminosity. The M dwarfs observed during Kepler's primary mission were much more massive—and, thus, more luminous—than TRAPPIST-1. This explains why Kepler did not see planetary systems like that orbiting TRAPPIST-1, despite the likely prevalence of such systems in the galaxy.

Other recently discovered rocky planets in the habitable zone include a planet orbiting in the outer habitable zone of the M-dwarf star LHS 1140 (12 pc away; Dittmann et al. 2017; Kopparapu et al. 2013). Feng et al. (2017) also published a re-analysis of Doppler data on Tau Ceti, a Sun-like star just 3.7 pc distant, which supports earlier claims that the star hosts two habitable zone worlds (Tau Ceti e and f) with minimum masses of about 4 Earth masses. Finally, Bonfils et al. (2017) announced the discovery of Ross 128 b, 3.4 pc distant, with a minimum mass of 1.35 Earth masses orbiting in the habitable zone of its parent M-dwarf star. Given the ubiquity of M dwarfs in the Milky Way, these nearby discoveries (summarized in Table 3.1) suggest that the galaxy is teeming with planets orbiting in their host star's habitable zones.

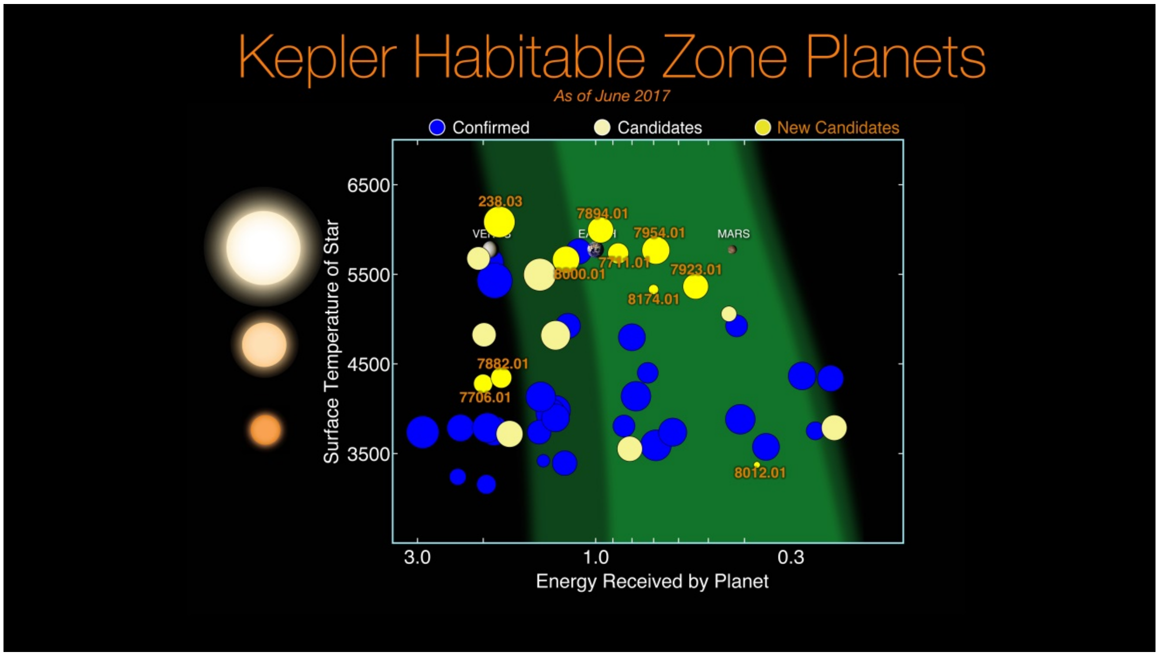

FIGURE 3.2 NASA's Kepler mission discovered approximately 50 planets within the habitable zone of their host stars (Thompson et al. 2017). Highlighted are new planet candidates from the eighth Kepler planet candidate catalog that are less than twice the size of Earth and orbit in the stars' habitable zone—the range of distances from a star where liquid water could pool on the surface of an orbiting Earth-like planet. The dark green area represents an optimistic estimate for the habitable zone, while the brighter green area represents a more conservative estimate for the habitable zone. The sizes of the colored disks indicate the sizes of these exoplanets relative to one another and to the image of Earth, Venus, and Mars, placed on this diagram for reference. Note that the new candidates tend to be around stars more similar to the Sun—around 5,800 K—representing progress in finding planets that are similar to the Earth in size and temperature that orbit sunlike stars. Data are from DR25, the final data release from Kepler's primary mission. SOURCE: NASA Ames Research Center/Wendy Stenzel.

> **Finding:** The discovery of numerous nearby exoplanets orbiting in their host star's habitable zone, coupled with estimates of the fraction of stars with terrestrial-size, habitable-zone planets has matured the search for evidence of life beyond the solar system enough to warrant taking the next steps toward its discovery.

As these recent discoveries show, M-dwarf planets will be at the vanguard of efforts to characterize exoplanet habitability because they are abundant and relatively easy to discover and characterize. This is due to a number of key factors, including the following:

- The smaller, dimmer parent star increases the detectability of a planet in both transmitted and emitted light relative to that of a similar body in orbit about a G-dwarf star;
- The compact nature of the habitable zone of an M-dwarf star means that planets orbiting therein are more likely to be seen transiting their parent star; and
- Planets in the habitable zone of an M-dwarf star have short orbital periods, allowing multiple transits to be observed in a relatively short period of time.

M-dwarf stars are also the most common type of star in the galaxy, comprising ~70 percent of the stellar population (Henry et al. 2018). Statistical results from Kepler show that early M-dwarf stars are more likely to have smaller, terrestrial-sized planets than Sun-like G-dwarf stars (Howard et al. 2011; Dressing and Charbonneau 2015; and Mulders et al. 2015) and that compact multiplanet systems may occur for at least 50 percent of M-dwarf stars (Ballard and Johnson 2016; and Muirhead et al. 2015). For example, as mentioned above, the nearby TRAPPIST-1 M-dwarf system has three planets found within the (conservative) habitable zone (Gillon et al. 2017). These results suggest that M-dwarf stars may harbor the most habitable zone terrestrial planets in the galaxy, potentially by a very large margin. It is also worth noting that Kepler/K2 and ground-based surveys are probing very different types of M–dwarf stars and, yet, both are finding that potentially habitable planets are common.

> **Finding:** The availability of near-term data on the atmospheres of terrestrial exoplanets orbiting M-dwarf stars will enable the first observational tests of their potential habitability.

Consequently, whether M-dwarf habitable zone planets are indeed habitable is a key question with important implications for understanding of the distribution of life in the galaxy. However, M-dwarf stars undergo a very different luminosity evolution track compared to more Sun-like G-dwarf stars, as the young M-dwarf star contracts more slowly to reach its main sequence size. During this pre-main sequence phase, an M-dwarf star's luminosity can be significantly higher than it will be on the main sequence, subjecting planets that inhabit orbits consistent with the main sequence habitable zone to much larger amounts of stellar radiation early on. For the smaller M–dwarf stars, this super-luminous pre-main-sequence phase can last for as long as a billion years (Baraffe et al. 2015) before the star contracts, dims, and joins the main sequence. During this phase, M-dwarf stars could strip planetary atmospheres and evaporating oceans via stellar X-ray ultraviolet (XUV) and extreme ultraviolet (EUV) radiation and the stellar wind (Dong et al. 2017; Garcia-Sage 2017). Even failure to lose a dense primordial atmosphere may inhibit or preclude their habitability (Owen and Mohanty 2016). The maintenance of a planetary atmosphere occurs through an interplay between atmospheric loss and atmospheric replenishment from outgassing and volatile delivery. Whether M-dwarf planets, after initially losing atmosphere and ocean, can regain them remains uncertain and remains a valuable line of research. Recent work has also shown that an increased understanding of stellar variability is crucial for optimizing exoplanet characterization (Morris et al. 2018) and that parameters such as metallicity and star age need to be constrained to inform planetary formation and evolutionary models and infer terrestrial exoplanet composition (e.g., Dorn et al. 2018). The evolution of stellar luminosity and XUV radiation are key to understanding planetary atmospheric retention, composition, and evolution (e.g., Luger and Barnes 2015). Additionally, characterizing the stellar energy distribution, especially in the ultraviolet wavelengths, is needed to understand the photochemistry that can enhance or destroy biosignatures (e.g., Segura et al. 2005; Rugheimer et al. 2015). In the near-term, observations with Atmospheric Remote-sensing Infrared Exoplanet Large-survey Ariel,[1] JWST (e.g., for the TRAPPIST-1 system and GJ 1132b; Meadows et al. 2018a) and large ground-based telescopes (e.g., Proxima Centauri b; e.g., Lovis et al. 2017; Snellen et al. 2015) may be able to address such questions about the coevolution of exoplanet atmospheres and surfaces with their host stars.

> **Finding:** Because of the coevolution of host star and exoplanet, stellar activity and evolution are critically important for understanding the dynamic habitability of exoplanets.

Assessing habitability of exoplanets requires observations of the parent star and, in particular, its spectral energy distribution and flare frequency and energy. Additionally, observations of the planet that probe the planetary atmosphere, and ideally the planetary surface, are also necessary. Using transmission observations, the stratospheres, and perhaps upper tropospheres of transiting planets like TRAPPIST-1,

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[1] For more information about Ariel, see http://sci.esa.int/ariel/.

are anticipated to be accessible. These observations could hold information about atmospheric composition, the presence or absence of water vapor in the stratosphere (Meadows et al. 2018a; Lincowski et al. 2018), the presence of clouds or aerosols (Arney et al. 2017), including volcanic products (Misra et al. 2016), and day-night temperature differences (Kreidberg and Loeb 2016; Meadows et al. 2018a). These observations may be possible in the near-term with JWST and ground-based telescopes.

TABLE 3.1 Masses and Orbital Properties of Relatively Nearby, Potentially Habitable Worlds

Planet Name	Distance (light years)	Discovery Method	Planet Mass Estimate Range (Earth masses)	Planet Radius Estimate Range (Earth radii)	Orbital Period (days)	Orbital Semimajor Axis (AU)	Host Star Type	Host Star Mass (solar masses)	Reference
Prox Cen b	4.2	Doppler	1.10-1.46 (min)	-	11.2	0.05	M5.5V	0.12	Anglada-Escude et al. 2016
TRAPPIST-1 d	40	transits and timing	0.14-0.068	0.742-0.802	4.05	0.021	M8V	0.080	Gillon et al. 2017
TRAPPIST-1 e	40	transits and timing	0.04-1.20	0.879-0.957	6.10	0.028	M8V	0.080	Gillon et al. 2017
TRAPPIST-1 f	40	transits and timing	0.50-0.86	1.007-1.083	9.21	0.037	M8V	0.080	Gillon et al. 2017
TRAPPIST-1 g	40	transits and timing	0.46-2.22	1.086-1.168	12.4	0.045	M8V	0.080	Gillon et al. 2017
LHS 1140 b	39	transits and Doppler	4.83-8.47	1.33-1.153	24.7	0.0875	M4.5V	0.146	Dittmann et al. 2017
Tau Ceti e	12	Doppler	3.29-4.76 (min)	-	163	0.538	G8.5V	0.783	Feng et al. 2017
Tau Ceti f	12	Doppler	2.56-4.98 (min)	-	636	1.334	G8.5V	0.783	Feng et al. 2017
Ross 128 b	11	Doppler	(1.30-1.45 min)	-	9.9	0.05	M4V	0.168	Bonfils et al. 2017

NOTE; Listed in order of the date of their discovery announcement or journal publication date.

In the longer term, direct imaging observations of planetary atmospheres and surfaces will be needed to build upon these initial transmission assays of planetary upper atmospheres, by probing near-surface atmospheres and constraining planetary surface conditions. Transmission observations are not an option for more Sun-like F-, G-, and K-dwarf stars, due to the larger stellar size and more distant habitable zone, which diminishes the planet signal and the probability that it transits its star. Direct imaging observations of F-, G-, and K-dwarf stars, will complement the near-term transmission observations of M-dwarf stars. These direct-imaging observations can also be used to search for water and biosignatures, which may be more detectable in the near-surface environment than in the transmission-probed upper atmosphere and to map the planetary surface using light curves and spectra to look for continents and oceans (Cowan et al. 2009). The initial assay of M-dwarf habitability using transmission observations with JWST and ground-based, high-resolution spectroscopy (Snellen et al. 2015; Lovis et al. 2017) will therefore be complemented and succeeded by direct imaging undertaken by more capable space telescope missions currently under study and by future 30 and 40 m ground-based telescopes (Quanz et al. 2015). These future capabilities will complement transmission observations of M-dwarf stars to provide a more complete census of the habitability of terrestrial planets orbiting a wide range of stellar hosts, and expanding the context of Earth’s habitability.

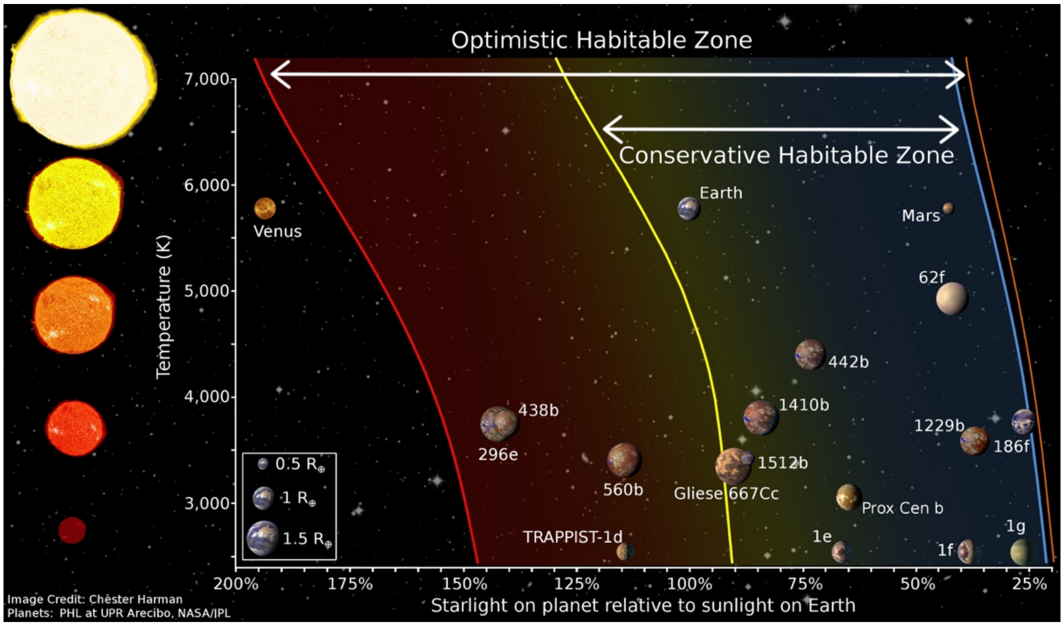

Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

FIGURE 3.3 Diagram of the habitable zone around the Sun and other stars. The x-axis represents the amount of starlight hitting the planet relative to that which hits modern Earth. The y-axis represents stellar effective temperature. Conservative and optimistic habitable zone limits are shown (Kopparapu et al. 2013). Proxima Centauri b and four of the TRAPPIST-1 planets are also shown. This diagram is older than Figure 2.7 and does not include some of the new G- and K-star planets shown there. Planets shown here are also smaller than 1.6 Earth radii, whereas Figure 2.7 contains planets up to 2 Earth radii. Note that the radii shown for non-transiting exoplanets (e.g., Proxima Centauri b) are theoretical estimates. SOURCE: Chester Harman.

EVOLUTION FROM HABITABLE ZONE(S) TO MULTI-PARAMETER HABITABILITY ASSESSMENT

For exoplanet studies, the first order assessment of habitability has been the habitable zone (Figure 3.3). As energy from the star and the essential elements for life are presumed to be common at the surface of rocky planets, surface water has traditionally been seen as the limiting resource for exoplanet habitability. Because exoplanets can only be probed by remote sensing, astronomers focus on exoplanets that possess surface water, which is in contact with the atmosphere, and which can support a surface biosphere that is more likely to be detectable. The criterion of focusing on surface water has historically been used to define the habitable zone (Shapley 1953; Strughold 1955; Huang 1959, 1960; Hart 1978, 1979; Kasting et al. 1993; Kopparapu et al. 2013). The value of such a definition is that interactions between the hydrosphere, rocky surface, and atmosphere of these planets might make signatures of their surface habitability and biospheres remotely detectable.

The habitable zone has become the first order assessment method for newly discovered exoplanets, and it has guided the development of large space-based telescopes that will search for potential habitability exoplanets. A planet in the habitable zone is not necessarily habitable, and its habitability cannot be inferred, but only observationally confirmed. However, based on current knowledge of terrestrial planetary processes, the habitable zone is useful to identify that region around a star where an Earth-like exoplanet is most likely to be able to support surface liquid water, compared to elsewhere in the planetary system. The surface liquid water in turn increases the probability that the exoplanet can host a surface biosphere, which would be more accessible to remote-sensing observations.

Identifying the habitable zone requires two readily observable characteristics—the planet's distance from its star (semi-major axis and eccentricity) and the type of star that it orbits. These parameters are combined with climate model-derived limits on the distance an Earth-like planet can be from its star and maintain water on its surface.

Previous work has attempted to significantly widen the limits of the habitable zone by invoking hydrogen greenhouses that might extend the habitable zone to an orbit equivalent to Saturn's in the solar system (Seager 2013). That would imply that nearly every star has a potentially habitable planet, however, and could lead us to underdesign future space telescope missions to search for them. Alternatively, a near-desiccated planet on which oceans are confined to the planet's polar regions has been invoked (Abe et al. 2011). This model allows the habitable zone to be moved in towards the star. Setting aside the question of how likely such planets are to exist, this possibility is dealt with in the "optimistic" habitable zone definition of Kopparapu et al. (2013), which extends well inside the inner boundary of the "conservative" habitable zone. Other work on redefining the limits of the habitable zone has looked at the habitable zone limits for terrestrial planets larger than Earth (Kopparapu et al. 2014) and used sophisticated general circulation models to understand climate limits for planets with different rotation rates orbiting M-dwarf stars (Yang et al. 2014; Kopparapu et al. 2017). Energy-balance climate models have been used to show that the outer regions of the habitable zone may be less temperate than previously thought because of limit-cycling behavior in which the planet's climate alternates between frozen and non-frozen states (Menou 2015; Haqq-Misra et al. 2016).

As useful as the habitable zone's first order assessment of potential habitability can be, many factors impact a planet's habitability. Thus, the habitable zone can be thought of as a two-dimensional slice through a far more complex, interdisciplinary, and multidimensional parameter space. Consequently, a planet's position in the habitable zone does not guarantee habitability, because aspects of its formation or evolution may preclude habitability. The field of exoplanet habitability assessment is now advancing to study the planetary, stellar, planetary system, and galactic parameters and processes that affect an exoplanet's potential for habitability and to identify their relative accessibility to observation and study. This new multiparameter habitability assessment synthesizes knowledge and observations from many different fields to provide a more comprehensive and powerful assessment of the likelihood of exoplanet habitability, thereby improving our ability to pick the best targets to search for life.

The most obvious example of a non-habitable habitable zone planet is one that formed with little or no water (Raymond et al. 2004, 2007; Lissauer 2007), or that lost oceans of water during its M-dwarf host star's super-luminous pre-main-sequence phase (Luger et al. 2015; Meadows et al. 2018a). Even if the initial conditions were favorable for life, the planet interacts with its host star and planetary system, and habitability can be enhanced or lost over time. A planet will interact and evolve with the spectrum, luminosity, and activity of its host star. The spectrum of the host star, interacting with the atmosphere, will define the surface radiation environment and drive compositional changes to the planet's atmosphere through atmospheric loss processes and photochemistry. The planet's initial composition, the delivery of volatiles, its orbital evolution, and the subsequent interior and atmospheric evolution are also influenced by interactions with other planets in the system, including giant planets, and asteroid and Kuiper belts. The masses, orbits, and migration history of jovian planets in particular are critical to understanding the potential habitability of rocky planets in a planetary system (Raymond et al. 2008), as jovians can affect volatile delivery to forming terrestrial planets (e.g., eccentric jovian planets can inhibit water delivery to forming rocky planets; Raymond et al. 2004, 2007).

Consequently, the habitability of a planet is governed by a complex interplay between planet, star, planetary system architecture, and the mutual evolution of these components over time. Additional examples include the importance of plate tectonics and the role of outgassing in counteracting atmospheric loss and generating the secondary atmosphere that we may see in our observations. Plate tectonics recycles volatiles forms of elements such as carbon and sulfur efficiently on modern Earth. However, volatile recycling may occur even on stagnant-lid planets (Foley and Smye 2018), so this habitability requirement may not be absolute. Habitability may also require continents and relatively shallow oceans (relative to the planet's radius) that allow for recycling of other biogenic elements like phosphorus. Phosphorus is supplied to the modern oceans almost entirely by weathering of continental rocks (Tyrell 1999); hence, it could conceivably be scarce on waterworlds with few or no emergent continents.

Understanding the factors that affect habitability will enable identification of those exoplanets that are most likely to be habitable and inform our interpretation of upcoming exoplanet data to be used to search for life beyond the Earth. The likely impact of relevant interactions, relationships, and evolution of these parameters on planetary habitability has also been studied more extensively in the past five years. For future observation target selection of habitable exoplanets, it will be important to develop a means of moving beyond habitability assessment based upon the traditional habitable zone alone. Rather, habitability potential will need to be assessed using as many of the characteristics and processes outlined in Figure 3.1 and those yet to be discovered, as can be observationally accessed or theoretically constrained. Preliminary steps in this direction have been taken by proposing habitability ‘indices’ that are observations of an exoplanet’s semi-major axis and a parameter sweep through the radiative and climatic impact of possible orbital eccentricity and planetary albedo to determine the probability of habitability within the habitable zone limits, e.g., the ‘habitability index for transiting exoplanets (HITE) (Barnes et al. 2015). Although these are steps toward a multi-parameter assessment for habitability, none of these initial attempts comprehensively models interactions between planet-star and planetary system, as constrained by observations, and so the concept of multi-parameter habitability assessment is still a very fruitful avenue for future research.

> **Finding:** The context of solar and planetary system architecture and evolution is important for determining a planet’s history of habitability and limits on habitability, and is important to inform target selection and exploration.

Another promising area currently being developed is that of intermodal complementarity and comparison for habitability assessment. Multi-model approaches are used in Earth science to constrain uncertainties in climate change (Taylor et al. 2012) and this approach is also relevant to other bodies in the solar system with atmospheres and to exoplanets where the range of stellar insolation and the spread of model results could be even larger (e.g., Popp et al. 2016). One-dimensional (1-D) and 3-dimensional (3-D) climate models have complementary strengths, applicability and computational expense, and can support each other for modeling the habitability of exoplanet environments by passing environmental variables that are best calculated by each model. One-dimensional climate codes generally do a more careful calculation of radiative transfer and gaseous absorption than 3-D general circulation models (GCMs) and can model a broader range of exoplanet atmospheric conditions and condensates (Robinson and Crisp 2017), but are most applicable to rapidly rotating planets. 3-D GCMs, in contrast, are excellent for modeling synchronously rotating planets orbiting M dwarfs where there is a strong day-night difference, and these models can self-consistently calculate the effects of water vapor, ice albedo and cloud feedback on climate, and simulate spatially-non-uniform phenomena that impact observations such as the formation of dayside clouds and day-night temperature. However, 3-D GCMs are computationally expensive and difficult to couple to chemistry models, so there are still applications where 1-D comparisons with the 3-D GCMs can be informative. Similarly, it is important to compare results from different 3-D models to each other to search for consensus in modeled phenomena, and increase confidence in the simulations. For example, the inner edge of the habitable zone is best determined by 3-D models because these models can account for changes in relative humidity and clouds. But the model predictions differ in their specifics: LeConte et al. (2013) predict that a runaway greenhouse would occur for a 10 % increase in solar flux relative to present Earth, whereas Wolf and Toon (2015), using a different GCM, find that runaway would require a flux increase of 21 %. In distance units, this puts the inner edge at 0.95 AU and 0.91 AU, respectively. While these differences may not seem large, they highlight the fact that not all climate models are the same and that simulating a wide range of planetary climates is a complex task.

Finding: Continued theoretical modeling of planetary environments, including model inter-comparisons, is required to explore processes, interactions, and environmental outcomes and to understand habitability and biosignatures in the context of their environment.

COMPARATIVE PLANETOLOGY

The discovery of over 3,700 confirmed planets beyond the solar system opens up an exciting opportunity to understand a diversity of planetary characteristics and processes. Many of these new worlds have no analog in the solar system and so can enrich knowledge of those characteristics of the planetary system, star, and planet that contribute to or detract from planetary habitability. Other exoplanet discoveries can be likened to planets within the solar system, for example planets GJ 1132b (Berta-Thompson et al. 2015) and TRAPPIST-1b (Gillon et al. 2016), which may have characteristics and processes in common with Venus and are thus labeled "exo-Venuses." Such comparisons provide impetus for the solar system and exoplanetary science communities to share expertise and collaborate on understanding planetary processes and evolution. On the one hand, the discovery of habitable zone, rocky exoplanets offers the exciting possibility to discover habitable environments that would place Earth in a cosmic context. If signs of life were detected on these planets, a new era of comparative astrobiology would begin. On the other hand, comparisons among the terrestrial planets within the solar system illuminate the divergent paths that terrestrial planet evolution can take both toward and away from habitability, or propose entirely different models of planetary formation, as with the ocean worlds. This is an increasingly rich area for future development.

Comparative Planetology of Solar System Planets

Presumably Venus, Earth and Mars formed from the same initial inventory of the solar nebula material. Isotopic and geological evidence suggest the presence of surface liquid water on all these planets in the past, along with plentiful solar and chemical energy and minerals for nutrients. Arguably the right conditions existed all three planets to be habitable in the past. Both Venus and Mars have masses and internal structures that differ from Earth's, and they occupy different distances from the Sun within the solar system's habitable zone. Their climate evolution in the past four billion years has led them on dramatically divergent paths, however. Today only Earth is undeniably habitable and inhabited, while Venus is hot and dry with a dense atmosphere and Mars is cold and dry with a thin atmosphere. For these reasons, Mars and Venus inform the search for life by improving understanding of the diversity of terrestrial planet evolutionary outcomes and illuminating how these outcomes influence habitability. Such diversity of habitable planets in the solar system may also exist in other stellar systems with multiple "habitable" planets as well. Their comparative planetology is going to be just as important to reveal whether life exists on any of them.

Mars: Another Habitable World?

Interest in Mars stems from the fact that amongst the planets in the Sun's habitable zone, the surface of Mars exhibits characteristics suggesting that it may have been more Earth-like in the past That leads to the question of whether microbial life ever existed on Mars in the past or survives today. Mars meets the minimum criteria for the existence of life: plentiful solar and chemical energy, surface water in the past (and possibly in the subsurface today) and nutrients, including CHNOPS (e.g., Grotzinger et al. 2014; Mahaffy et al. 2015; Ehlmann et al. 2016). The detection and variability of methane in the atmosphere of Mars (Webster et al. 2015, 2018) and the detection of organic molecules (chlorobenzene and dichloropropane) in the martian surface (Freissinet et al. 2015; Eigenbrode et al. 2018) indicate processes of carbon geochemistry not previously anticipated, however, their origin could well be geologic or exogenous. Current techniques have not been able to discriminate between the biogenic and abiotic origin of the martian molecules reported to date. The European Space Agency (ESA) Trace Gas Orbiter promises to determine the carbon-isotopic ratio in methane and the abundances of the heavy hydrocarbons such as ethane, which would help with this question but is unlikely to resolve it beyond doubt (Olson et al. 2017). The Mars Organic Molecular Analyzer (MOMA; Goesmann et al. 2017) on the future ExoMars rover may also address this question by looking look for organics from depths of up to 2 meters. As the early Mars cooled it evolved from a period of active plate tectonics to the current epoch of a single global plate forming a stagnant lid over a convecting mantle (e.g., Bruer and Spohn 2003). Thus, one question the planet poses is: for how long could a one-plate planet host life? NASA's InSight mission, launched in May 2018, is anticipated to reveal answers to questions concerning Mars' internal structure and level of geodynamic activity.

Venus: The End State of Habitable Planet Evolution?

Despite its location on the inner edge of this solar system's classically-defined habitable zone and receiving twice the solar insolation as does Earth, early Venus is thought to have hosted a global ocean early in its evolution and may have been as habitable as the early Earth. An enhanced D/H ratio in the venusian atmosphere, however, suggests that the planet suffered a runaway greenhouse effect (Watson et al. 1981; Donahue et al. 1982) resulting in the loss of its ocean (deBergh et al.,1991). Furthermore, desiccation of the atmosphere and surface may have inhibited subduction, fused the crustal plates, and extinguished the interior dynamo (Nimmo et al. 2002). Such a chain of events would have exposed the Venus atmosphere to predation from the solar wind, and the processes Venus underwent to reach its current state may define the inner edge of a star's habitable zone.

The heating of Venus and the loss of its ocean allow the study of processes that reduce planetary habitability and may even represent the trajectory of Earth's own, continuing evolution. Furthermore, current methods in exoplanet detection favor detection of planets on the inner edge of their star's habitable zones—much closer to Venus's position than to Earth's (Kane et al. 2018). Thus, the exploration of Venus is important, not only for understanding the evolution of planetary habitability, but also as an analog to habitable zone exoplanets. In the last five years, major discoveries by the ESA Venus Express and Japan Aerospace Exploration Agency (JAXA) Venus Climate Orbiter Akatsuki have revealed key processes in the venusian atmosphere related to atmospheric and water loss, ozone formation, temperature structure, and magnetoprotection (see, for example, Markiewicz et al. 2007). Venus' atmospheric chemistry shows many intriguing features, including unexpectedly efficient recombination of photolyzed carbon dioxide and thus little formation of abiotic oxygen. Further, Venus' slow rotation and rapid atmospheric superrotation provide clues to processes that may drive other high-irradiation worlds or enhance habitability on tidally-locked worlds. Looking into the future, there is much to be learned not only about Earth, but also about exoplanets, from Venus.

Ocean Worlds: Comparing Surface and Subsurface Oceans

Some of the most exciting recent work in the ocean worlds community has come from comparing these bodies to each other. In addition to their surface differences, the available Galileo and Cassini datasets allow for comparisons to be made between ocean worlds based upon their internal structure. Despite similar sizes, comparisons place the large, icy, ocean moons along continua defined by ocean depth and pressure effects (low-density Enceladus to high-pressure Ganymede), activity (from fully-resurfaced Europa to heavily-cratered Callisto), or differentiation (from fully-differentiated Europa to partially-differentiated Titan) (Schubert et al. 2010; Iess et al. 2012, 2014). These comparisons provide a first-order glimpse into the effects of planetary size, formation, and tidal activity on putative habitability.

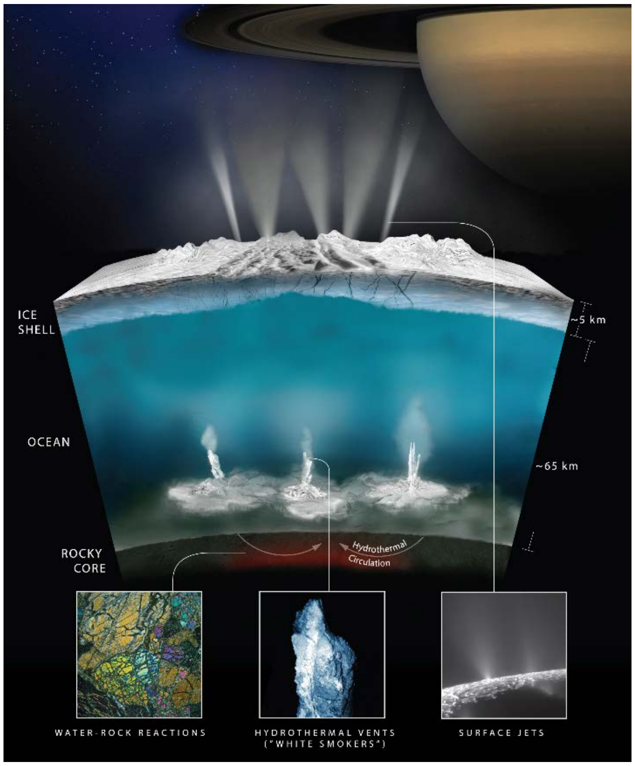

FIGURE 3.4 Chemical evidence consistent with serpentinization and water-rock interactions on Enceladus and known hydrothermal activity make Enceladus a key target for astrobiology exploration. Sampling the moon's plumes would help to establish if life exists there now. SOURCE: NASA/JPL-Caltech/Southwest Research Institute.

The discovery of potential plumes on Europa has driven comparisons with Enceladus, a moon for which the ocean composition is better known because of its regular plume expression (Figure 3.4). Studies of both of these potentially habitable environments complement each other. While the differences between these bodies are significant, confirmation of modern serpentinizing conditions on Enceladus despite its lower tidal and radiogenic heating suggests that Europa could host similar processes. Moreover, Cassini demonstrated that the ocean composition and putative habitability of Enceladus could be measured using a combination of mass and dust spectroscopy of particles emitted from the planet (e.g., Postberg et al. 2006; Waite et al. 2017). This has informed the exploration strategy for Europa and driven improvements to the instruments selected for Europa Clipper, including the ability to measure the europan atmosphere and sample potential plume ejecta in the search for longer chain carbon molecules that may provide insight into biological versus abiotic processes (Pappalardo et al. 2018). In return follow-on missions to Enceladus have proposed using the improved Europa Clipper approaches to attempt life detection at Enceladus using high-resolution mass spectrometry of plume samples (Lunine et al. 2015; Lunine 2018).

The recent emphasis on comparing moons has resulted in community prioritization of a mission to the neptunian, rather than the uranian system, as Triton has more indications of geologic activity and potential habitability that any of the uranian moons (OPAG 2015). Furthermore, comparative moon studies have enabled stronger bridges between the planetary and Earth oceanography communities, as progress in understanding the habitability of ocean worlds hinges on comparisons with terrestrial processes such as serpentinization (e.g., MacDonald and Fyfe 1985; Mayhew et al. 2013; Vance et al. 2016), hydrothermal vents and ocean pH (e.g., Hsu et al. 2015, Glein et al. 2015), and circulation and ice-ocean interactions (e.g., Craven et al. 2009; Vance and Goodman 2009; Soderlund et al. 2014). This has enabled parallel technology development for instrumentation and strategies for measuring and interpreting signals from these worlds. Accessing the subsurface of the ocean worlds is a challenge unlike any yet encountered on another celestial body. Today, this challenge is being explored in Earth's analog polar regions. Development of underwater and through-ice capability on a wide range of platforms, including for the Earth's poles, is enabling scientific advancement, driving instrument and sampling development while bridging technological gaps in communication, navigation, and autonomous integration. The development path relies heavily on integrating science and engineering seamlessly to optimize for dealing with challenging environments while achieving critical science goals. Looking into the future, however, similar expeditions could explore deep within the icy ocean shell, within a water cavity, or in the ocean below.

Comparative Planetology within the Exoplanet Populations

The wealth of newly discovered exoplanets has allowed statistically significant comparisons between populations of exoplanets that have challenged existing models and expanded understanding of planet formation and evolution beyond the planets in the solar system. These new data have revealed unexpected processes, such as migration, that may have been key mechanisms for volatile delivery during Earth's formation. Comparisons between size, density, and distance from the parent star have informed atmospheric escape processes (Lopez and Fortney 2014; Owen and Mohanty 2016) and improved understanding of which planets are more likely to be rocky (Rogers et al. 2015; Weiss et al. 2014). Statistical studies of Kepler's M-dwarf population suggest that multi-planet systems may be very common, with many small planets in the habitable zone (Ballard and Johnson 2016; Gillon et al. 2017). While early studies of exoplanets focused on detection, and the recent plethora of planets has informed demographics, exoplanet science is moving into an era in which rocky exoplanets are being initially characterized. Theoretical models of rocky planet formation and evolution, including the maintenance or loss of habitability and volatile transport within forming planetary systems will soon be confronted with new data on the atmospheric compositions of a number of potentially habitable worlds, leading to theoretical refinements incorporating those observations.

The Kepler mission revolutionized knowledge of exoplanet demographics and has helped to determine the frequency of potentially habitable worlds around sunlike and low mass stars (G-, K-, and M-dwarfs). Kepler's data and recent discoveries of nearby habitable zone worlds using ground-based observations (Muirhead et al. 2015; Anglada-Escudé et al. 2016; Gillon et al. 2016; 2017; Dittmann et al. 2016) have ushered in a new era of comparative planetology for habitable zone planets. Radii, masses, and densities are now being measured for habitable zone planets around nearby M-dwarfs (Gillon et al. 2017; Grimm et al. 2018; Dittmann et al. 2016). These planets are likely rocky, although the densities (Grimm et al. 2018) and corroborating evidence of migration (Luger et al. 2017) suggest that these planets may be more volatile rich than rocky planets in the solar system. These planets also likely underwent significant atmospheric evolution due to the long, early brightness of M-dwarf stars, a phase that is much shorter for G-dwarfs like the Sun. As a result, they may have lost oceans (Luger and Barnes 2015) and acquired oxygen- or carbon dioxide-dominated atmospheres (Meadows et al. 2018a). The first attempts at probing the atmospheric composition of these small habitable zone planets with Hubble Space Telescope, Spitzer, and ground-based telescopes (Delrez et al. 2018; deWit et al., 2018, Southworth et al. 2017) have provided broad constraints that can only rule out hydrogen-dominated atmospheres, although future technologies will have the ability to do more.

Additionally, with increasing technological capacity, exomoons and exorings provide constraints on exoplanet formation mechanisms as well as the bombardment history of planetary systems and the potential delivery of volatiles (Heller 2017). Current transit timing and duration techniques have provided potential methods for exomoon and exoring detections (e.g., Kipping et al. 2012; Arnold and Schneider 2004; Teachey et al. 2018) that will be employable with upcoming space and ground-based transit programs.

Solar System and Exoplanet Synergies in Comparative Planetology

Recent acquisition of observational constraints on the atmospheres of habitable zone exoplanets opens a new interdisciplinary field of comparative planetology for habitable zone planets. The potential for growth is large and requires expanded collaboration between scientists studying bodies in the solar system and those who observe and model exoplanets. Interdisciplinary, cross-divisional collaborations between NASA-supported planetary scientists and exoplanet astronomers can be facilitated by research coordination networks (see "Programmatic Challenges and Opportunities Related to the Search for Life in the Universe" in Chapter 5).

Observations of the distant Earth from interplanetary spacecraft have informed our understanding of remotely detectable signs of habitability and life and observing strategies for future exoplanet characterization telescopes (Lustig-Yaeger et al. 2017). Additionally, exoplanet science has greatly expanded the known diversity of planet types and planetary architectures and has provided insights into planet formation, migration, and evolution that have directly impacted understanding of the solar system's early evolution in dynamics and composition (e.g., Walsh et al. 2011). In turn, the solar system provides information on planetary processes for nearby targets that can be studied in more detail than will be possible for exoplanets. In the near term, such processes include tidal forces on Jupiter's moons as analogs for tidal heating in exoplanet systems (Jackson et al. 2008; Heller et al. 2014) and analog geometries that inform exoplanet observing techniques, such as Titan solar occultations as analogs for exoplanet transmission spectroscopy (Robinson et al. 2014).

Shared themes between solar system small bodies and exoplanet studies are also providing synergistic links between solar system and exoplanet scientists. Studies comparing water and its isotopes, gases, and organic material between comets, asteroids, the Kuiper belt, and the scattered disk reveal how such materials incorporate into planets during formation or are delivered later. Achievements made by the European Space Agency (ESA) Rosetta mission at comet 67P/Churymurov-Gerasimenko informed the structure and evolution of comets and their dust and ice materials. Further, the mission encountered black radiation-resistant organic polymers at the surface of the comet and the presence of a large variety of molecules, including amino acids and even a sugar-precursor (Goesmann et al. 2015).

The Dawn mission to asteroid 1 Ceres detected ice in surface exposures (Combe et al. 2016), in the global crust (Prettyman et al. 2016), and within specific geological features including landslides and impact ejecta (Schmidt et al. 2017). Moreover, relatively high albedo features within the floor of Occator crater (e.g., Krohn et al. 2016, Scully et al. 2018, Bowling et al. 2018), were suggested to be consistent with the presence of hydrated salts (DeSanctis et al. 2016). While it is unlikely there is a modern ocean, a volatile-rich crust and deeper mantle could have undergone active water-rock reactions early in its history or during recent impact events.

Together, these findings suggest that ongoing small-body processes may have also impacted the veneer of materials, including volatiles and organics, delivered to the Earth and other planets in the solar system. The influence of solar system architecture on small-body inventories and how it might impact volatile and organic delivery has bearing on studies of planetary systems. Together with observations of debris disks and protoplanetary disks, which represent the evolution between scattered planetesimals and evolving planetary systems, such observations help constrain which exoplanets may be volatile-rich and how those volatile inventories have evolved.

The solar system planetary community can also provide atmospheric, surface, and interior models as well as a systems science approach to interpreting data from terrestrial exoplanets (Meadows et al. 2018a). The Earth can continue to serve as an analog for habitable exoplanets, and understanding the environments of the Earth through time provides a series of examples of alien habitable environments for which we have geochemical and biological constraints. Venus also has a role to play in understanding of biosignature interpretation, as its carbon dioxide and oxygen catalytic chemistry can inform our understanding and models of the likelihood of false positive biosignatures on worlds that experience high irradiation. Meanwhile Titan may serve as an analog for exoplanets with hazy atmospheres (Trainer et al. 2018). Understanding of the evolution this planetary system with its G-dwarf host star will serve as a key comparison for what will be learned about M-dwarf planet evolution from upcoming exoplanet observations.

Finding: Comparative planetology between the solar system and exoplanetary systems is:

- A powerful approach to understanding the processes and properties that impact planetary habitability;
- Essential to inform experiments, modelling, and mission planning in astrobiology; and
- Fundamentally requires cross-divisional collaboration between astrobiologists, planetary scientists and exoplanet astronomers and is, therefore ideally suited to a research coordination network.

BOX 3.1
Life as We Don’t Know It: The Case for Habitability of Titan

There are at least two approaches to thinking about life as we *don’t* know it. The first is to consider how different life can be from terran life while still being carbon-based and requiring a water solvent. The second is to consider a life that is not carbon-based, does not require water, or both. Saturn’s largest moon, Titan, has provoked much speculation about the possibility of life in a hydrocarbon solvent (McKay and Smith 2005; Schulz-Makuch and Grinspoon 2005; McKay 2016; Cable et. al 2018; Malaska et al. 2018).

Although Titan’s surface lacks water due to its low temperature (94 K), liquid hydrocarbons (primarily methane and ethane) condensed from the atmosphere make up the vast lakes and seas observed by the Cassini-Huygens mission (Hayes 2016). A thick (1.5 bar) nitrogen and methane atmosphere contains a number of key volatiles including hydrogen, ethane, acetylene, propane, benzene, polyacetylene, polycyclic aromatic hydrocarbons, and nitriles such as hydrogen cyanide and acrylonitrile (Wilson and Atreya 2004). Many of these deposit on the surface. This organic-rich surface is replete with carbon, hydrogen, and nitrogen, together with a meteoritc influx of metals similar to those required for terran biochemistry—iron, copper, zinc, nickel, magnesium, manganese, calcium, and sodium, may contain the ingredients for life as we don’t know it. It has been suggested a putative surface biosphere could be fueled by the hydrogenation of acetylene (McKay and Smith 2005), or potentially even sunlight, which even at 0.1% compared to Earth’s surface, might be sufficient for a Titan-version of photosynthesis though it is not a prerequisite for life on Titan given the preponderance of hydrocarbons (McKay 2016). A global liquid hydrocarbon cycle complete with evaporation, condensation, rain-out, and transport (Atreya et al. 2006; Lunine and Atreya 2008), akin to Earth’s hydrologic cycle, could serve to recycle surface materials and replenish a putative surface biosphere. Another potential habitat for life on Titan that has been discussed is the water ocean tens of kilometers beneath the icy crust (Iess, et al. 2014). This briny ocean comprised of sodium, sulfur, and potassium (Mitri et al. 2014) and rich in ammonia serves as a second potential habitable target for life as we don’t know it.

Scant observational evidence is presently available to test hypotheses regarding habitability and life on Titan, either in the liquid methane-ethane reservoirs on the surface or the water ocean beneath. Widespread microorganisms likely would deplete hydrogen and acetylene, but the Huygens landing site shows little evidence of this. The situation may be more favorable in the methane-ethane lakes and seas in Titan’s polar regions, as the equatorial landing site of Huygens was barely wet with methane. The confirmed detection of acrylonitrile molecule in Titan’s atmosphere by ground-based telescopes presents a tantalizing possibility that metabolites of any living microorganisms might survive under the extreme cold temperatures of Titan. Layers of acrylonitrile deposited on the surface have the potential to form cellular-like compartments, analogous to the lipid bilayers of cell membranes in terrestrial organisms (Palmer et al. 2017). Discerning signs of life in the subsurface ocean will be more challenging compared to the accessible regions at the surface and in the atmosphere, however, active cryovolcanism may deliver to the surface material from the interior.

Statistical Methods for Comparative Planetology

A wide range of problems in astrobiology have benefited from recent progress in statistical methods. Planetary evolution is a complex set of nested processes and timescales that combine to produce the end state of the planet. Statistical methods for comparative planetology allow information to be extracted from large or complex data sets, and probabilistic approaches can be utilized to assess how the likely scenarios may unfold, and to evaluate likely end points (Bean et al. 2017). Such approaches are providing a common theme across planetary science, astrophysics, heliophysics, biosignatures, Earth science, and stellar astronomy. This interdisciplinarity is contributing to astrobiology moving more effectively toward understanding complex systems, be they life itself, an ecosystem of multiple interdependent species and environmental conditions, or a planet with a complex geological and atmospheric cycles with input from the host star. Statistical methods provide a fundamental capability that allows astrobiologists to compare and collate diverse data into a framework that enable testing of hypotheses and model development within and across disciplines (e.g., Clanton and Gaudi 2017; Schwartz and Cowan 2015). Such tools include but are not limited to Monte Carlo methods that sweep through solution space, cluster analysis that assesses the relationship of data points to each other, nearest neighbor assessments, which weight the importance of close versus distant data values, Bayesian frameworks, which describe the conditional dependencies of various inputs upon each other, and network theory, which represents nodes and relationships in maps of data. For habitability, these approaches may offer the chance to integrate wide-ranging types of data into a single model as well as to assess the relative importance of various elements into the end result. For studies of biosignatures (see next section), these approaches can produce information about associations between genes or organisms. For biomarkers, such techniques can assess the relative value of various biomarkers within a given system or determine whether a measurement of non-terran materials contains information consistent with life—for example, by determining if a methane lake on Titan contains evidence for non-water based life (Box 3.1).

> **Finding:** Techniques based on statistical methods, scaling laws, information theory, and probabilistic approaches are useful in other branches of science and are increasingly being applied in the search for life.

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4

Biosignature Identification and Interpretation

Traditionally, biosignatures have been defined as an object, substance, and/or pattern whose origin specifically requires a biological agent (Des Marais et al. 2003). The compendium of features listed by Des Marais et al. (2008) includes, but is not limited to:

- Cellular and extracellular morphologies;
- Biogenic fabrics in rocks;
- Bio-organic molecular structures;
- Chirality;
- Biogenic minerals;
- Biogenic stable isotope patterns in minerals and organic compounds;
- Atmospheric gases;
- Remotely detectable features on planetary surfaces; and
- Temporal changes in global planetary properties.

In order to qualify as biosignatures these "*features must be sufficiently complex and/or abundant so that they retain a diagnostic expression of some of life's universal attributes"* (Des Marais et al. 2008). Another essential characteristic is that their formation by non-biological processes be highly improbable. Informational biopolymers like DNA or polypeptides, for example, would be examples of biosignatures that are highly unlikely to arise in the absence of biology.

The past 20 years has seen a major evolution in biosignature science. The evolution is summarized in the following statement from the Report of the Mars 2020 Science Definition Team (Mustard et al. 2013):

> The scientific significance of any potential sign of past life comes not only from the probability of life having produced it, but also from the improbability of non-biological processes producing it.
>
> Report of the Mars 2020 Science Definition Team

These concepts govern the selection of candidate biosignatures, which are ranked by how well they pass three criteria: reliability, i.e., a feature that is more likely to be produced by life; survivability, i.e., the ability of the biosignature to be preserved or otherwise persist in its environment; and detectability, the likelihood that the biosignature can be observed or measured (NASEM 2017; Meadows 2017; Meadows et al. 2018b).

So far, only the Viking mission has conducted a rigorous search for in situ biosignatures on another planet, focused on metabolic indicators of life, including the search for organic compounds (Biemann et al. 1977; Klein 1978). After a hiatus of more than four decades, a NASA mission concept is being developed—a Europa lander—whose top priority is the search for life (Hand et al. 2018). This new search for life is spurred by the idea that the search for life by future missions will be likely to benefit from a broader definition of life, with the search focused on the function of biochemical processes (Chyba and Phillips 2001).

The Galileo spacecraft, while on route to Jupiter, searched for biosignatures on Earth using remote sensing techniques. Signs of life were found during Galileo's flyby of the Earth in December of 1990. Purported biosignatures on Earth comprised the detection of gases, in this case methane and oxygen, in strong thermodynamic disequilibrium (Hitchcock and Lovelock 1967). The thermodynamic disequilibrium of Earth's atmosphere was interpreted to imply a continuous and large surface flux of both gases. Additional biosignatures included surface reflectance signals due to vegetation and narrow-band pulse-modulated radio signs (Sagan et al. 1993). While abiotic processes may be identified that can produce disequilibria and narrow-band radio signals (Renno and Ruf 2012), as a suite, the planetary characteristics identified by Galileo are strongly suggestive of an inhabited planet. The Earth continues to be studied for the nature and detectability of its biosignatures, and significant work is underway to develop the telescopic capability to search for life on exoplanets. These future searches in the solar system and beyond will need to be supported by significant new research on biosignature identification and interpretation.

Since publication of the 2015 Astrobiology Strategy, the field of biosignature research has advanced four major areas: 1) the search for and identification of novel biosignatures, especially those that are agnostic to life's molecular makeup or metabolism, 2) a concerted effort to better understanding abiosignatures (signature of abiotic processes and phenomenon), in particular those that may mimic biosignatures, 3) an improved understanding of which biosignatures are most likely to survive in the environment, and at what timescales of preservation, and 4) the first steps toward developing a comprehensive framework that could be used to interpret potential biosignatures, abiosignatures, false positives, and false negatives, and increase confidence and consensus in interpretations. This work has progressed in parallel for both in situ biosignatures, (e.g., those preserved in rock or ice that can be searched for on the surface of Mars or Europa), and in remotely-sensed, often global-scale biosignatures that might be observed telescopically in the atmospheres or surfaces of exoplanets, or detected on solar system bodies by orbiter or flyby spacecraft. For remotely-sensed biosignatures, a comprehensive series of review papers on the topic of exoplanet biosignatures and future directions (Schwieterman et al. 2018; Meadows et al. 2018b; Catling et al. 2018; Walker et al. 2018; Fujii et al. 2018) was published as part of a Nexus for Exoplanet Systems Science (NExSS) community-wide biosignatures workshop activity (Kiang et al. 2018).

Identifying Novel Biosignatures to Improve Reliability

The search for life is constrained by the ability to recognize life's impact on its environment—a biosignature. Recent research has identified new ideas for both in situ and global, remote-sensing biosignatures and advanced a new area of research into agnostic biosignatures. Agnostic biosignatures are those that are not tied to a particular metabolism informational biopolymer, or other characteristic of life as we know it, but which may manifest as unexpected complexity either in a system-wide alteration of a planetary environment or in preserved molecules.

The in situ search for biosignatures typically focuses on microbial life because microbes are more pervasive than multi-cellular organisms. Indeed, diverse and complementary indicators of biological activity, including the enantiomeric and isotopic distribution of organic compounds, are useful (e.g., Lovelock 1965, 1975). These compounds can be measured using mass spectrometry, gas-chromatography mass spectrometry, evolved gas analysis, Raman spectroscopy and culture-based methods (e.g., Summons et al. 2008). The presence of organic compounds does not prove the existence of life because complex carbon-containing molecules are readily generated abiotically. Rather, a chemical biosignature is the presence of specific patterns in the abundances of selected compounds that do not typically occur via chance in reactions driven by thermodynamics alone. Microscopy can provide another line of evidence, for instance if motile microorganisms are present in a sample (e.g., Seo et al. 2010; Ha et al. 2015; Bedrossian et al. 2017). DNA-based surveys are also being proposed for in situ searches for Earth-like biosignatures (e.g., Carr et al. 2016). Because microbes on Earth thrive in brine inclusions in sea ice, which also contain nutrients and organics in high concentration (Junge et al. 2001), brine inclusions would be an excellent target for the search for biosignatures and life in cold worlds. However, continued developments in identification of novel biosignatures for in situ life searches are still needed, including an improved understanding of potential biosignatures for icy worlds, subsurface organisms, and chemoautotrophic microorganisms.

> **Finding:** The catalog of potential biosignatures would benefit from a systematic re-evaluation and increased understanding of the nature and detectability of biosignatures, especially for in situ detection of energy-starved or otherwise sparsely distributed forms such as chemoautotrophic and subsurface life.

Novel remote-sensing biosignatures for exoplanets, that were recently identified include the formation of hazes in anoxic environments due to methanogenic production of CH_4 well above that expected from geological processes such as serpenitinzation (Arney et al. 2018), work in progress on identifying a range of volatile molecules that could potentially be biosignatures (Seager et al. 2016), seasonality in gas abundances as a biosignature (Olson et al. 2018), and identification of unusual global disequilibria. While the simultaneous presence of O_2 (or O_3) and CH_4 (or N_2O) is still a compelling remote biosignature, recent research has sought to identify other potential disequilibria that might indicate life. These include the presence of ammonia on hydrogen-dominated worlds (Seager and Bains 2015), the combination of both O_2 and N_2 and the presence of an ocean on a habitable world (Krissansen-Totton et al. 2016), or the simultaneous presence of N_2, CH_4, CO_2, and liquid water, and/or methane mixing ratios greater than 10^{-3}. The latter biosignature is potentially biogenic due to the difficulty in maintaining large abiotic methane fluxes to support high methane levels in anoxic atmospheres (Krissansen-Totton et al. 2018).

While thermodynamic disequilibrium can be abiotically generated, most often by photochemical and other planetary processes, the biosignature is not the thermodynamic disequilibrium itself, but rather the fluxes inferred to drive that disequilibrium. As such, thermodynamic disequilibrium does not have to presuppose a particular metabolism and can be considered agnostic. The classic Earth O_2/CH_4 disequilibrium provides an example. In the context of the atmospheric composition, volcanic outgassing, and the stellar ultraviolet spectrum, O_2 has a geologic lifetime of ~2 million years, while CH_4 and N_2O have photochemical lifetimes of ~12 and ~150 years, respectively. This means that the latter two gases, in particular, are fluxed into the atmosphere at a high rate, or else they would disappear almost immediately. If these fluxes are particularly high, they can identify a more likely biological than planetary source. This is the case of Earth's microbiallly generated CH_4, which is more than 60 times higher than the estimated abiotic flux from water-rock reactions on Earth (e.g., Etiope and Sherwood Lollar 2013), and photosynthetically-generated O_2, which has a flux many orders of magnitude higher than photochemical production of O_2 for the Earth around the Sun.

AGNOSTIC BIOSIGNATURES

In addition to this expanded study of global thermodynamic disequilibrium, there have been considerable recent advances in the field of agnostic biosignatures (Johnson et al. 2018a,b). These advances explore specific frameworks and techniques for universal life detection that do not presuppose any particular molecular framework (Cronin and Walker 2016) or evolutionary endpoint (Cabrol et al. 2016). While the current field of novel biosignature identification for in situ biosignatures focuses on structures believed to represent life as we know it—particular classes

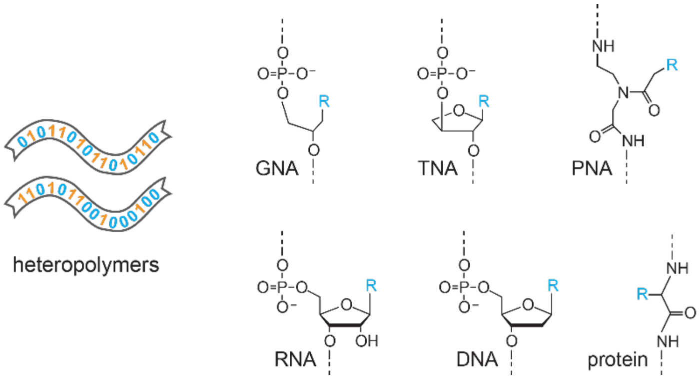

FIGURE 4.1 Informational heteropolymers would be strongly indicative of biological processes if they contain at least two subunits (R = 0, 1). They do not need to be linear. In terrestrial biology these molecules are RNA (R = A, C, G, U), DNA (R = A, C, G, T), and protein (R = Ala, Arg, Asn, Asp, etc.). Related molecules that have been studied in the laboratory include GNA (glycol nucleic acid), TNA (threose nucleic acid), and PNA (peptide nucleic acid), but a much broader variety of informational heteropolymers are chemically plausible.

of molecules or isotopic signatures, chirality, or molecular weight patterns for fatty acids or lipids—the goal for the emerging field of agnostic biosignatures is to expand the ability to search for life as we do not know it through exploration of a broader definition of life based on activity, with less dependence on assumptions about structure and specific biogeochemistry (Johnson 2018). Discussion focuses on a variety of approaches including but not limited to consideration of general molecular complexity associated with observations of matter and energy transfer as well as conceptualization of the number of pathways by which a given molecule can be assembled and the probability of its formation in the absence of biology (Cronin and Walker 2016; Marshall et al. 2017). Statistical analysis and combinatorial chemistry including machine learning and computational models and algorithms to estimate the probability for disequilibrium are the foundation of this approach (Keefe et al. 2010; Goodwin et al. 2015). Defining molecular complexity not simply based on molecular size or type but rather on detecting assemblages of molecules that are abiotically improbable is a key approach to this research. Other approaches consider elemental and/or isotopic gradients or accumulations distinct from the surrounding environment, as well as disequilibrium redox chemistry inconsistent with the abiotic environmental baseline.

Example: From Terrestrial Genetic Code to Agnostic Biosignatures

A hallmark of living systems is the perpetuation of genetic information reflecting the history of the system's adaptive responses to the environment. For all known cellular organisms this information is stored in nucleic acid molecules (e.g., Figure 4.1). It is also transiently represented as RNA transcripts and protein translation products. If the goal of an in situ life detection experiment is to detect Earth-like life, or terrestrial contaminants (see Box 6.2) thereof, then the powerful technologies of nucleic acid amplification and sequencing can be applied (see Box 5.1). These technologies require minimal deviation from the canonical structure of DNA or RNA. For alternate forms of life, however, it is important to consider how to detect informational molecules more generally. Arguably, the detection of heteropolymers (i.e., polymers that contain more than one type of subunit) that have an "aperiodic" composition (Schrödinger 1944) would be strongly indicative of biological processes. Such a composition would be witnessed as the non-uniform spatial arrangement of monomeric subunits within a linear (or perhaps two- or three-dimensional) polymer (and potentially agnostic biosignature).

Considering the in situ detection of informational heteropolymers more broadly, it will be essential to develop techniques that are agnostic to the detailed chemical composition of the informational heteropolymer. It has been suggested that a linear genetic polymer operating in an aqueous environment is highly likely to be a polyelectrolyte (Benner 2017). Thus, it may be advantageous to devise capture and detection methods based on the regular spacing of positively or negative charged subunits. Slight variation in the spacing of subunits might be indicative of heterogeneous composition of the polymer and perhaps the presence of genetic information content. Note that such an approach would apply not only to the genetic material itself, but also to corresponding transcription and translation products that contain a preponderance of charged subunits. It may not be possible to achieve precisely-matched spacing of complementary charges in the detector. However, even if the detector is out of frame relative to the polymer, the phase mismatch between polymer and detector will be discernable, so long as the spacing is regular.

Whether or not the genetic material is a polyelectrolyte, there are other potential approaches for determining whether it has a heteropolymeric composition. Both matrix-assisted laser desorption/ionization time-of-flight (MALDI-TOF) mass spectrometry and liquid-chromatography tandem mass spectrometry (LC-MS/MS) have been used to fingerprint proteins and other heteropolymers. The former technique requires relatively pure samples and therefore would not be suitable for in situ detection unless the materials could first be selectively captured on a surface or enriched by some other means. The latter technique relies on liquid chromatography to first separate the materials prior to mass analysis. In both cases, sample material is typically pre-processed by enzymatic digestion to generate a library of fragments that can be matched to a database of known fragments of the same material. No such database exists for the detection of previously uncharacterized heteropolymers, but the goal of in situ life detection studies is to determine whether informational heteropolymers are present, not the particular ordering of subunits within those heteropolymers.

The generalized detection of informational heteropolymers can be accomplished using mass spectrometry methods (e.g., Arevalo et al. 2015). If the bonds between polymeric subunits undergo spontaneous cleavage in the mass spectrometer, then fragmentation is achieved “on the fly” and the degree of fragmentation can be modulated by adjusting the voltage of the instrument. This approach has been used to detect and even sequence synthetic informational heteropolymers where the subunits are joined by labile alkoxyamine groups (Al Ouahabi et al. 2017). For an unknown heteropolymer one cannot rely on fragmentation between subunits in the mass spectrometer. Instead it will be necessary to apply a standard set of pre-processing steps that aim to achieve partial fragmentation, then compare the spectra of intact and partially fragmented samples. The fragmentation processes might include shear force (forced flow through a narrow aperture), sonication, and acid or base hydrolysis.

The task of in situ detection of a heteropolymer of unknown composition is not an easy one. However, it provides the opportunity to detect biosignatures that are very unlikely to arise through abiotic processes. The ultimate signature of life is information, written in the language of molecules. Whether that information is the product of extinct or extant life, simple or complex life, it is a distinguishing feature that is worth pursuing. In support of these efforts, there is substantial research activity in the area of synthetic biology that considers alternative genetic polymers and functional macromolecules. There too, analytic methods are challenging, but are being addressed by various techniques that may prove applicable to in situ detection.

The above comments notwithstanding, the detection of DNA (or RNA) heteropolymers is an essential part of biosignature detection, both because the opportunity exists for a common form of life within the solar system and because the technology for such detection is highly mature. As a cautionary note, it is important to recognize that the detection of ancient DNA samples (>1 million years old) is highly problematic, even for the most pristine samples on Earth. DNA is susceptible to both chemical and enzymatic degradation, making its detection and analysis even more challenging for remote instrumentation.

For remote-sensing, agnostic biosignatures may take the form of atmospheric disequilibria, as discussed previously, or the presence of complex chemical networks in a planetary atmosphere. In both cases, significant environmental context will be needed to interpret the disequilibria or chemical networks as a sign of life, including quantification of the biosignature gas and other gases in the atmosphere, knowledge of the stellar spectral energy distribution, including the ultraviolet, and photochemical and climate models that can be used to constrain the fluxes of gases required to maintain the disequilibrium. In addition to disequilibria, the community is now considering how biosignatures can be quantified using a Bayesian framework that can generalize search strategies beyond the biosignatures of known life. This Bayesian methodology will help quantitatively define the conditional probabilities and confidence of future life detection, and may constrain the prior probability of life even without a positive detection. (Walker et al. 2018).

> **Recommendation: The search for life beyond Earth requires more sophisticated frameworks for considering the potential for non-terran life, therefore, NASA should support research on novel and/or agnostic biosignatures.**

BOX 4.1
Viruses and Astrobiology

The intersection of viral research with astrobiology is an emerging field that touches on the origins and evolution of life and the detection of life on Earth (Berliner et al. 2018). Viruses, as known to exist in terrestrial biology, are small infectious agents that reproduce only inside living cells. They typically comprise a DNA or RNA genome in a protein capsid, sometimes covered by a lipid/protein envelope. Although viruses are usually considered to be non-living because they lack the basic biological machinery of even the simplest cells, they can have genomes larger than those of some bacteria (Schultz et al. 2017) and are vital components of the biosphere.

Ancient viruses may have played roles in major evolutionary transitions such as the development of DNA genomes from an ancestral RNA world (Forterre 2005), the divergence of Archaea from Bacteria (Forterre and Prangishvili 2009; Prangishvili 2013), and the origin of the eukaryotic nucleus (Bell 2009). Modern viruses participate in biogeochemical cycles, for example by lysing marine microbes, thereby releasing a large reservoir of organic carbon for recycling in deep-sea ecosystems (the so-called *viral shunt*; Danovaro et al. 2008, Bidle and Falkowski 2004).

If cellular life exists beyond Earth, it seems reasonable to suspect that virus-like entities may exist as well. This has given rise to the concept of “Astrovirology” – a term coined by Barry Blumberg, the founding director of the NASA Astrobiology Institute and Nobel Laureate discoverer of the Hepatitis-B virus. A primary challenge of this field of research is to determine what signatures of viral activity are detectable on Earth and potentially beyond. For example, the metabolic activity of marine microorganisms produces isotopic fractionations that can be used to study biogeochemical cycles (e.g., Peterson and Fry 1987). Marine bacteria infected by certain viruses, however, may produce different isotopic fractionations due to altered metabolic processes (Anantharaman et al. 2014; Roux et al. 2016).

One might adopt a broader view of what constitutes a “virus” when considering the possibility of extraterrestrial life. A cellular or acellular organism might exchange genetic information through a variety of mechanisms where the exchanged information itself becomes the object of evolutionary optimization and innovation, thereby contributing to the diversity of life.

SURVIVABILITY OF BIOSIGNATURES

Arguably, the question of survivability and preservation, especially on a global planetary scale, in the rock record and in the atmosphere, and on planetary timescales that may extend to billions of years has received less attention than research into biosignature reliability and detectability. At the present time, Earth analog studies and modelling approaches appear to be two of the most practical ways to shed light on taphonomic issues—namely biosignature formation, preservation, alteration and destruction—as they relate to planetary exploration and the search for life.

Record Bias

For the better part of Earth's history life was entirely microbial, devoid of mineralogical hard parts, and with little in the way of recalcitrant and preservable biopolymers. Those records of early life that do exist are fragmentary and, likely, highly biased. For example, cherts are sometimes fossiliferous while sandstones rarely are. As a consequence, fossil hunters target cherts, sometimes to the exclusion of other lithologies, thereby leading to strong biases in the paleontological and astrobiological literature. Improved understanding of the mechanistic aspects of fossilization processes and environmental conditions that are particularly favorable for fossil formation and preservation has long been an agenda item in biosignature research with potential to uncover records that have previously been overlooked. Over the past few years, there has been an evolving landscape in terms of understanding how long habitable environments comprising lakes, seas, groundwater, and subsurface fluids might have existed on Mars (Ehlmann and Edwards 2014; Grotzinger et al., 2015 Science; Goudge et al. 2016; Ehlmann et al. 2016). On Earth, preservation of subsurface fluids providing a habitable subsurface environment rich in electron donors and acceptors has been recently shown to extend to more than a billion years (Holland et al. 2013; Li et al. 2016; Warr et al. 2018).

Preservational Bias

Understanding taphonomic biases is particularly important for environments and times when fossils are exclusively microscopic, such as in the Archean, and requires painstaking work. Whether addressing microbial life on the early Earth or Mars, a common assumption is that organisms that can be preserved are abundant in the environment. However, this situation is relatively rare, as shown by a recent study in which hundreds of meters of core were screened to detect a centimetric-scale horizon of brucite-calcite veins. These veins preserved biosignature lipids and microfossil remnants of a Cretaceous serpentinizing system in the seafloor near the Iberia margin (Klein et al. 2015). With all the modern tools available for studies of biosignatures for a hydrothermal ecosystem on Earth, this particular report illustrates the very difficult problem of looking for life that is not abundant. The challenges would be orders of magnitude more difficult on Mars.

One of the most interesting signatures of planetary bodies is the isotopic composition of minerals, especially with respect to CHNOPS,[1] the six key biogenic elements that are incorporated into the macromolecules of life on Earth. Metabolism of organisms leads to "waste" products that are incorporated into minerals and kerogens and are potential biomarkers of past life. Indeed, the isotopic record of stable carbon isotopes in Earth's geological record, especially in carbonates, has been used to infer the oxidation state of this planet. Similarly, the pattern of sulfur isotopes has changed over geological time on Earth, and has been used to infer when the atmosphere of Earth contained ozone, a gas that cannot exist in a planetary atmosphere without molecular oxygen. Secular changes in nitrogen isotopes in kerogens can be used to infer the oxidation state in aquatic systems. However, these and other isotopic "signatures" can be overprinted by (e.g.) hydrothermal fluids, metamorphism and other geological processes. Similarly, the valence state of transition metals, such as Mo and Cr can be diagenically altered, leading to a misinterpretation of the oxidation state of the environment at the time of deposition. Hence, it is highly desirable to perform redundant analyses of several isotopes of minerals

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[1] Strictly speaking CHNOS, because phosphorous has only one stable isotope.

FIGURE 4.2 (Left) Plan-view of domal stromatolites from the 3.45 Ga Pilbara Strelley Pool Formation. SOURCE: Roger Summons. (Right) Cross-sectional view of stromatolites from the Strelley Pool Formation. SOURCE: Frances Westall.

and/or kerogens (when available) to provide more conclusive evidence of past or present life on planets and planetary bodies within the solar system.

On Earth, the preservation of ancient biosignatures is largely attenuated by tectonic processes including the thermal metamorphism that accompanies burial, together with uplift and erosion that can destroy them completely. Crustal fluid flow and contact with radioactive minerals are other deleterious factors. Recycling of sedimentary rock via plate tectonics has destroyed much of Earth’s early crust. Although this is perceived to be less of a factor for Mars, the cratering record indicates that volcanism has contributed to significant re-surfacing. Even the large expanses of ancient rock on Earth (> 70% of the exposed surface area of continental lithosphere is Precambrian in age with approximately 14% of that Archean versus 86% Proterozoic; Goodwin 1996) have typically been heated to temperatures that confound preservation of biosignatures and abiosignatures and reset many parameters of interest.

Nonetheless, there are some locations where thermal conditions (French et al. 2015) may have been low enough on billion year timescales for isotopic biosignatures (Li et al. 2016), and fluid components (Holland et al. 2013; Warr et al. 2018) to survive. Careful examination of such opportunities from Earth analogs (even if rare) will provide important test beds for expanding our understanding of biosignature preservation in ancient rock-hosted systems at low temperatures that may be relevant to Mars.

Studies of the sedimentary rock record on Earth have shown that favorable conditions for capturing and preserving microstructures and molecular biosignatures include rapid burial in fine-grained, detrital sediments (mudstones and shales) that experience early cementation by stable secondary phases, commonly silica and carbonate (e.g., Westall et al. 2015a,b; Knoll and Golubic 1979; Hofmann 1976) and sulfate evaporites (Westall et al. 2011b; Schopf et al. 2012). These early diagenetic processes can enhance the detail of preserved fossils and textures and also reduce the permeability to crustal fluids during later burial and diagenesis, thus protecting organic matter from oxidation. Most organically-preserved cellular remains observed in the Precambrian fossil record on Earth formed by these basic processes (e.g., Knoll 2003, 2012; Farmer and Des Marais 1999; Javaux et al. 2010). On Earth, such preservation is also observed in saline lake environments where evaporation forms brines. Mineral precipitation results from fluids that are characterized by a broad range of salinity and temperature conditions that are also observed the Mars (Barbieri and Stivaletta 2011).

Biosignature preservation is observed in thermal spring environments over a broad range of temperature, pH, and redox conditions (Campbell et al. 2015). Where springs deliver effluents rich in minerals (e.g., silica, carbonate, iron oxides, evaporites and clays), organisms may be quickly entombed in the mineral deposits and preserved as a wide range of biosignature types including cellular permineralization, millimeter- to centimeter-scale microfabrics, and microbially mediated mesoscale structures (including stromatolites) (Figure 4.2). Examples of potential hydrothermal spring deposits and evaporites and clay-rich mudstones have been identified on Mars by landed and surface mission and an example, 'Home Plate,' has been proposed as potential landing sites for Mars 2020 (Ruff and Farmer 2016).

Despite decades of investigation, numerous controversies and disagreements are a pervasive aspect of research into the fossil record of the early Earth. Perhaps the most prominent example concerns the biogenicity of microstructures found within the Apex Chert of the Pilbara Craton of Western Australia (Schopf 1993) where there has been continual questioning of the original interpretations (Brasier et al. 2002) and a series of responses that continue to the present day (Schopf, and Kudryavtsev 2009; Schopf 2006; Schopf et al. 2018; Marshall et al. 2011). Given the lack of consensus, some of the oldest described microstructures fall into the categories of dubio-fossils (e.g., Wacey et al. 2016) or pseudo-fossils (Wacey et al. 2018). Other microstructures from Archean sediments from the Pilbara in Australia and Barberton in South Africa are suggested to represent biotic features (e.g., Hickman-Lewis et al. 2016). In all cases the kerogenous structures and their encasing sediments were rapidly encapsulated in hydrothermal silica. The predominant type of microstructure identified comprises fabrics suggestive of biofilms and microbial mat fragments that contain traces of organic matter in the form of kerogen. The deformable nature of these films, their diaphanous, web-like structure, and their typical particle-trapping characteristics have been deemed difficult to produce by abiotic means. This point is balanced against the complex and uncertain setting of the cherty beds of the Apex Formation at Chinaman Creek, in which pseudo-fossils were detected (Brasier et al. 2011; Marshall et al. 2014; Hickman-Lewis et al. 2016; Westall et al. 2011, 2015a,b). Nanoscale technologies such as nanoSIMS and laser Raman microspectroscopy are proposed to provide solutions to the uncertainties about the biogenic origin of Archean microstructures (e.g., Delarue et al. 2017). There is a pressing need however for these to be rigorously tested on a range of materials and matrices, including well-characterized microscopic fossils, before application to controversial objects. Until then, the capabilities of these technologies require a certain level of skepticism.

The influences of post-burial processes on biosignature retention, under different conditions, are not well understood at the microscale or nanoscale, making it hard to generalize about the expected impacts on preservation bias. The deleterious effects of heating organic matter during burial or volcanism are relatively well understood, for example. Consistent with the relatively high degree of thermal metamorphism, there is no extractable organic matter preserved in Archean sediments known to have retained features that can be attributed to primary biological origins (French et al. 2015). Ancient amorphous kerogens, on the other hand, appear to be more promising archives for the generating molecular biosignatures that could allow discrimination between biologically-derived and abiogenic organic matter. Catalytic pyrolysis under a stream of high pressure hydrogen (hydropyrolysis; Love et al. 1995) is one promising approach that has recently yielded evidence for the biological origin of some Archean kerogens (Duda et al. 2018). Organic matter in the 1.85 Ga old Gunflint Formation, which has experienced catagenetic temperatures of ∼150–170°C, still contains amide groups derived from protein compounds (Alleon et al. 2016). At a younger date, the 700-800 My old Draken Formation from Svarlbard (or Spitzbergen), which shows no sign of significant metamorphism, contains beautifully preserved carbonaceous cyanobacterial fossils with which are still associated biominerals, including pyrite, apatite and metastable opal (Foucher and Westall 2013). The ~400 My old Rhynie Chert, on the other hand is an example in which entombment in a subaerial hydrothermal spring has led to preservation of some of the oldest terrestrial flora and the associated microbial community (Edwards et al. 2018). However, the deposit has been thermally metamorphosed to the extent that the plant remains are "coalified." Although the silicified microbial and plant remains retain stunning morphological detail, and still contain organic matter comprising aromatic and aliphatic structures (Abbott et al. 2018) the heating regime has been so intense that there are no molecular diagnostic biosignatures that can be confidently attributed to any specific component of the ecosystem.

Lessons from the terrestrial record can provide us with an indication of the range of organic preservation that could be detected on Mars, as well as the methods and potential difficulties involved in the analysis of the organic matter (e.g., Westall et al. 2015q; Alleon et al. 2016). Because Mars has been accumulating meteorite-borne organic matter (Flynn 1996; Benner et al. 2000), and because abiotic organic synthesis on early Mars cannot be ruled out, the presence of organic phases alone is insufficient to identify their origins. Additional textural, chemical, and isotopic indicators, as well as the contextual parameters of the system are needed so that the potential for in situ abiotic or biotic synthesis can be evaluated. With respect to survivability, oxidative aqueous alteration and cosmic ray exposure are the primary factors over Mars' history that are destructive to organic matter. The former is best mitigated by selecting samples for which the mineralogical and textural properties would have minimized or precluded fluid flow (Farmer and Des Marais 1999). The latter, oxidative radiation, can be mitigated through careful subsurface sampling protocols that might avoid these taphonomic effects. (e.g., Gaboyer et al. 2017). New findings from the Curiosity rover have demonstrated that macromolecules, mineral interactions and permeability reduction that may have limited the exposure of organic, including thiophenic, acomatic, and aliphatic compounds, recently to migrating fluids and gases may all play a role in preservation of the organics recently reported for the 3.5 billion year old Murray Formation (Eigenbrode et al. 2018).

DETECTABILITY OF BIOSIGNATURES

Although biosignature preservation is an important consideration for molecular in situ biosignatures, "false negatives" can challenge remote-sensing and in situ biosignatures alike. False negatives occur when the environment in which the biosignature is produced or preserved is able to sufficiently suppress or overwhelm the biological signal so that it is undetectable. For remote-sensing biosignatures the classic example of a false negative is the suppression of the rise of photosynthetically-generated O_2 in the early Earth's atmosphere.

False Negatives and the Rise of O_2

Oxygen is the best-studied remote-sensing biosignature, with several false positives and their observational discriminants already identified (Meadows 2017; Schwieterman et al. 2018). Biosignatures are most robustly interpreted in the context of their environment, and the in-depth study of oxygen's false positive and negative scenarios provides a framework for assessing future biosignature candidates (Harman et al. 2015; Meadows et al. 2018b; Catling et al. 2018). Constraints from stable isotopes and trace element proxies indicate the evolution of oxygenic photosynthesis on Earth by at least ~3.0 Ga (Planavsky et al. 2014a) and perhaps much earlier (Rosing and Frei 2004). However, complementary isotopic constraints indicate that Earth's atmosphere was pervasively reducing until ~2.5 Ga (Farquhar et al. 2001; Pavlov and Kasting 2002; Zahnle et al. 2006). There thus appears to have been a significant period on Earth during which oxygenic photosynthesis was present but large amounts of O_2 did not accumulate in Earth's atmosphere. In addition, there is some evidence that after the initial accumulation of O_2 in Earth's atmosphere at ~2.3 Ga, atmospheric O_2 levels remained relatively low for much of the subsequent ~2 billion years (Planavsky et al. 2014b; Cole et al. 2016; Tang et al. 2016a). During this period, biogenic O_2, though clearly present, may have been challenging to detect remotely given current technology (Reinhard et al. 2017).

These studies of the rise of Earth's oxygen suggest that whether a planet develops a biogenic O_2-rich atmosphere will depend on both the evolution of oxygenic photosynthesis as well as geochemical dynamics at the planetary surface that are favorable for the long-term accumulation of a large atmospheric O_2 inventory (e.g., Gebauer et al. 2017). If planetary conditions are not favorable, then a false negative will occur. These dynamics will, in turn, depend on a series of planetary factors that may be challenging to constrain observationally or from first principles. For example, heat flux from a planetary interior (as constrained by radiogenic element inventory and planet size), oxygen fugacity of the planetary mantle (as constrained by both initial chemistry and long-term recycling of materials from the surface), the degree of crustal differentiation (as constrained by both overall heat fluxes and planetary rheology), and ocean chemistry can interact to buffer atmospheric O_2 to low levels despite the presence of oxygenic photosynthesis. The ability to constrain these contextual variables via observations of the planet and star, or via modeling, may ultimately form a critical component of target selection for exoplanet biosignature searches, and diagnosing false negatives for O_2 on living planets. Similarly, they lay the foundation for critical thinking on the nature and use of contextual information for other proposed biosignatures.

False Negatives in Low Energy Systems

Much of what we know about biosignatures is based on investigation of abundant and robust ecosystems, typically on the Earth's surface, in marine sediments, or in the relatively young (< 200 Ma) ocean floor subsurface (D'Hondt et al. 2009; Inagaki et al. 2015). Oligotrophic and or electron-acceptor limited marine sediments provide vital context about life metabolisms and rates in low energy flux systems (D'Hondt et al. 2009) inhabited by organisms with exceedingly slow growth rates (Trembath-Reichert et al. 2017). Additional information is increasingly being sought from other low energy systems, including extant life in fracture-controlled systems in ancient crystalline rocks of millions to billions of years in age, where energy flux is not only low but intermittent in space and time due to processes of storage and interconnection between fractures (Lin et al. 2006; Sherwood Lollar et al. 2007; 2104). Fracture controlled production of energy for chemolithotrophic life, and the rate of release of such energy due to fracture openings and propagation are particularly relevant to mission planning for Mars (Onstott et al. 2006) and for ocean worlds such as Europa and Enceladus (Vance et al. 2016).

While Earth's biological processes can provide robust signatures, if life is ephemeral in time or space, restricted to subsurface refugia or other oases, existing under conditions of slow maintenance energy, or even only as spores or other dormant or survival modes, biosignatures may be impossible to detect against the predominant abiotic baseline. The investigation of abiotic processes has sometimes been limited to the concept of establishing the abiotic (geological, chemical, physical) baseline or environmental context for biosignatures research. An emerging recent theme has been a more advanced approach that emphasizes identifying the spectrum of abiotic processes that mimic biosignatures; as well as those that may unambiguously identify abiotic processes (e.g., abiotic organic synthesis of methane or hydrocarbons). Energy flux is also a critical constraint on metabolic and biosynthetic rates as well as rates of abiotic destruction and attrition. Hence the abundance of molecules—the net result of their rates of production, accumulation, and transformation or destruction—is critical to whether or not biosignatures can accumulate to produce a detectable signature in an environment (Hoehler 2018; Cabrol et al. 2018). A classic example is the use of enantiometer excess (i.e., a preference of a system for the right- or left-handed versions of certain molecules) which may well be a biosignature, but which is consistently being interconverted abiotically to produce a more even mixture of right- and left-handed versions (racemization) and thereby erasing the signature of life. In an environment where energy flux is low, abiotic racemization may overwhelm the rate at which the biosignature is replenished by life (NASEM 2017). More generally, in oligotrophic environments, low rates of accumulation can mean the abundance of biosignatures (whether chemical, isotopic, mineralogical or morphological) is insufficient to detect above a baseline of competing physical, chemical or geological processes. The biological needle in an abiotic haystack will be difficult to identify and can lead to a false negative. Though less likely on Earth, some deep subsurface terrestrial habitats have been identified where such considerations are important (Sherwood Lollar et al. 2006; Moser et al. 2003), and certainly beyond Earth, such scenarios may predominate.

> **Finding:** Although suggestive of life and worthy of follow-on investigation, thermodynamic disequilibrium may result from a range of abiotic and biological processes and is therefore not always a biosignature.

Recommendation: NASA should support expanding biosignature research to addressing gaps in understanding biosignature preservation and the breadth of possible false positives and false negative signatures.

TOWARDS A COMPREHENSIVE FRAMEWORK FOR INTEGRATION OF BIOSIGNATURES

While novel biosignature identification expands the field of search opportunities, a comprehensive framework for assessing biosignatures in the context of their environment, and the use of multiple lines of evidence, allows progressively increasing confidence in the ability to detect of life. A rigorous understanding of the contextual setting provides clues that support or cast doubt on the authenticity of a biosignature, if they can be read and understood correctly. Since the 2015 Astrobiology Strategy there has been a growing realization of the importance of false positives, or abiosignatures—abiotic planetary processes that can mimic biosignatures, even for biosignatures like O_2 that were previously believed to be “robust” and have no known abiotic means of production.

It has now become apparent that it is not enough to simply search for a biosignature, but an understanding of environmental processes that might result in false negatives and false positives needs to be developed to choose those environments most likely to express a robust biological signal. In some cases, a biosignature may be an enhanced abundance over an abiotic background, as discussed above, and so knowledge of the feasible maximum of abiotic production of the signal also needs to be known. In addition, there is a better appreciation of the importance of combining multiple measurements to improve our confidence that a given biosignature is indeed due to life. While to a degree the logical strategies to address such issues have been available for > 20 years (e.g., from paleontologists contemplating how to deal with prokaryotic problematica; Hofmann 1972; Cloud 1973), these issues have been a major emerging theme in recent astrobiology discussion.

False Positives for Morphological Biosignatures

The issue of false positives is not a problem when dealing with morphologically complex multicellular organisms such as plants or animals with skeletons or biomineralization. It can be confounding, however, when the organisms comprise simple shapes like spheres or filaments with no distinct morphology or associated mineral. For example, the recent literature is replete with reports of potential biosignatures, however, a number do not ultimately withstand critical assessment (e.g., Bell et al. 2015, Djokic et al., 2017, Dodd et al., 2017, Nutman et al. 2016). The multitude of controversial biosignature reports detracts from widely accepted authentic records of Earth’s biota, and it often takes several years for critiques of *problematica* to appear, if they ever do. Some efforts have been made to systematically address the topic for the most ancient microscopic fossils using state-of-the-art microspectroscopic, microchemical and imaging approaches (e.g., Westall et al. 2011; Wacey et al. 2012; Wacey 2014), but more research could be directed toward multidisciplinary approaches to discriminating between ‘positives’ and ‘false positives’ in all classes of biosignature.

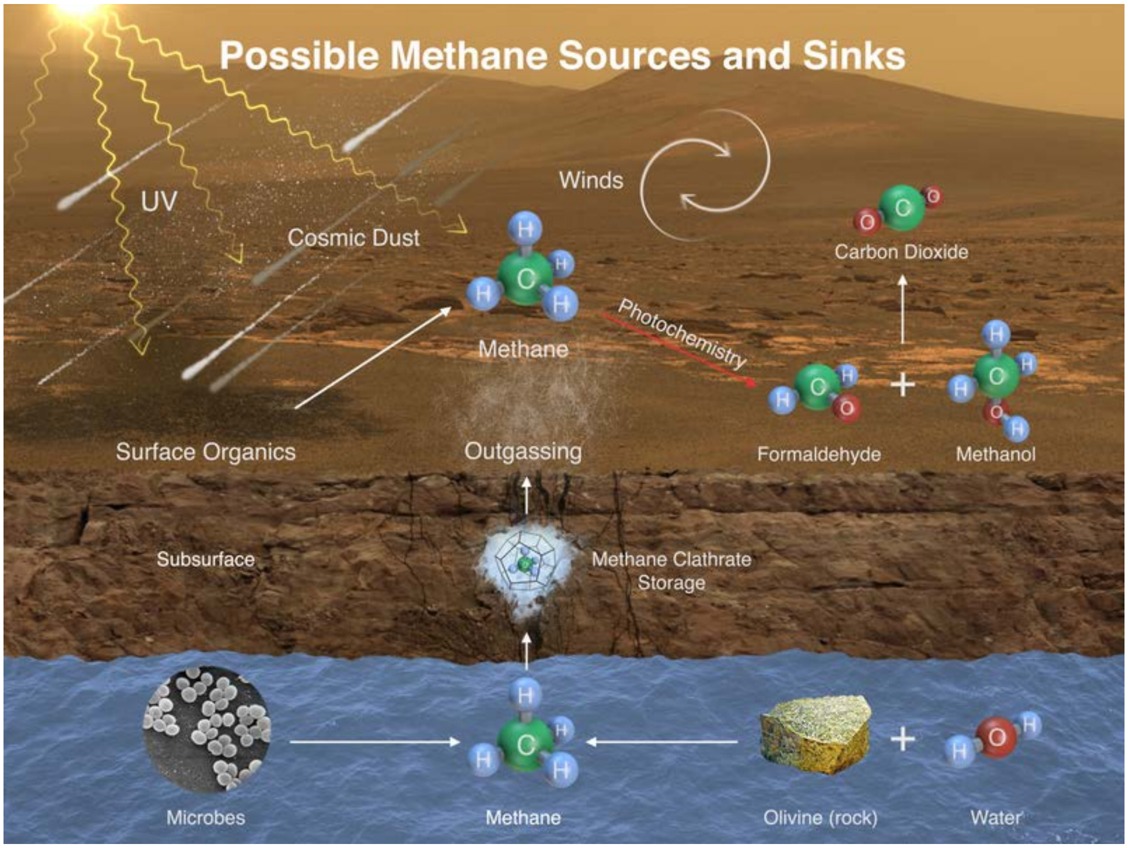

FIGURE 4.3 Illustration of possible processes relevant to the methane cycle on Mars. SOURCE: NASA/JPL-CalTech/SAM-GSFC/University of Michigan.

Research into laboratory-based chemical systems (Garcia-Ruiz et al. 2002, 2003, 2009) and natural environments prone to production of microscopic objects that mimic microbes (pseudo-biosignatures) (Barge et al. 2015a,b, 2016) is an emerging field that will inform biosignature studies in general. Isotopic biosignatures and microfossils are two additional areas where incomplete knowledge or failure to recognize or understand existing work can lead to false positive findings. In the case of isotopic biosignatures, equilibrium isotopic fractionations can overlap with the kinetic fractionations induced by biological processes (Bottinga 1969; Galimov 2006). Further, kinetic fractionations associated with abiotic organic synthesis have been shown to produce fractionations of comparable scale to those produced by kinetically-controlled biological processes (Horita and Berndt 1999; McCollom and Seewald 2006; Taran et al. 2007; McCollom et al. 2010). This insight has important implications for instance for resolving the origin of methane (Figure 4.3), as even on Earth the traditional concept that biologically-produced methane would be uniquely depleted in heavy carbon isotopes versus methane produced by abiotic processes, has been refuted (review by Etiope and Sherwood Lollar 2013). Similarly, for both terran (Mathez et al. 2918) and meteorite studies (Steele et al. 2012) it has been demonstrated that even organic carbon with “light” carbon isotope values requires careful contextual investigation of the microstructure of minerals and fracture infillings between and across those mineral boundaries to determine the abiotic versus biotic nature of macromolecular carbon. Accordingly, abiotic explanations need to be excluded through detailed analysis of context before isotopic biosignatures are accepted as robust. Ideally, contextual evidence including multiple and discrete biosignatures, and the elimination of potential abioisgnatures, would accompany claims for the ‘oldest life’ on Earth or for life detection beyond the Earth.

Finding: Re-examining controversial biosignatures from Earth's early sedimentary rock record can provide an important test-bed for biosignature assessment frameworks.

False Positives for the O_2 Global Biosignature

Since publication of the 2015 Astrobiology Strategy, multiple research groups have discovered mechanisms that could produce abiotic O_2 and O_3 in an exoplanet's atmosphere, especially in the atmospheres of those exoplanets orbiting M-dwarfs. Each presents a potential false positive to different degrees. Two of the proposed mechanisms allow water to enter a planet's stratosphere where it is photolyzed and the hydrogen atoms lost to space, resulting in O_2 buildup in the planet's upper atmosphere (Figure 4.4). Water entering the stratosphere could be enabled by loss of an ocean in a runaway greenhouse process (Luger and Barnes 2015)—a mechanism that is most effective for late-type (i.e., less massive) M-dwarfs. Alternatively there could be a lack of non-condensable gases in the planetary atmosphere, which could affect planets orbiting stars of any spectral type (Wordsworth and Pierrehumbert 2014). The runaway mechanism could produce an O_2-dominated atmosphere of hundreds of bars. The lack of non-condensable gases could potentially result in atmospheres that are ~15% O_2. It has also been suggested that Earth-like quantities of O_2 could be generated by the splitting of liquid water by a surface TiO_2 photocatalyst (Narita et al. 2015).

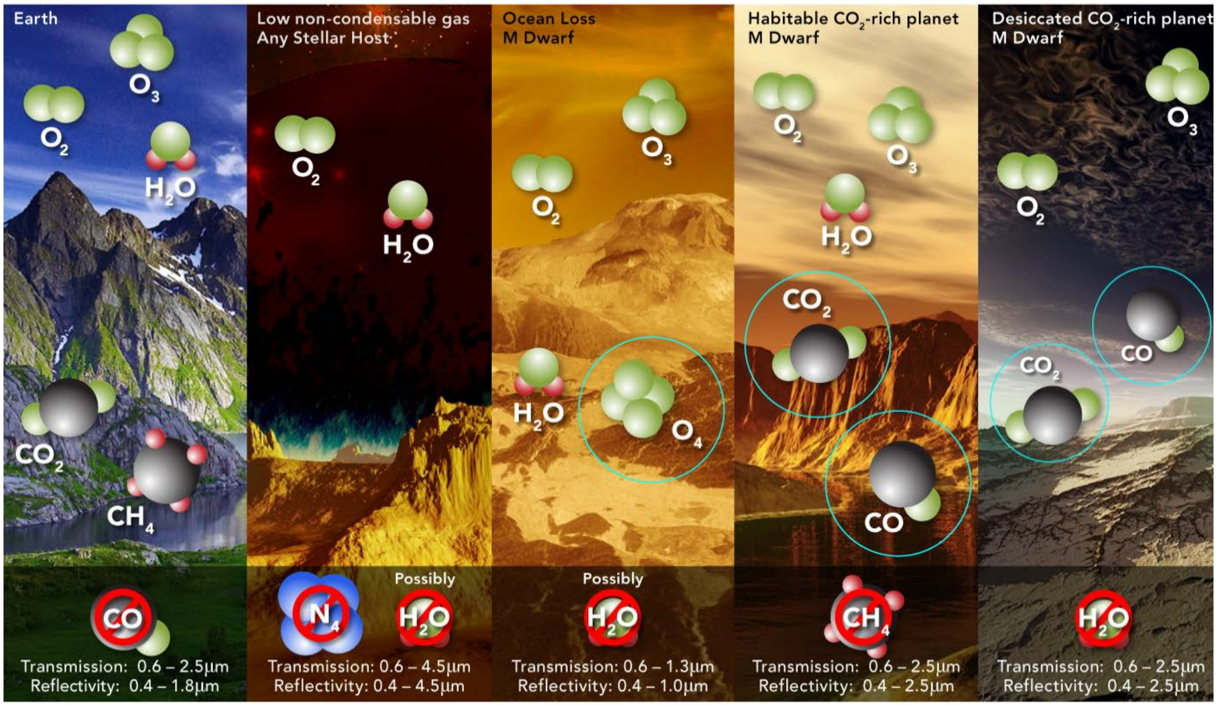

FIGURE 4.4 False positives (abiotic planetary processes) for O_2 generation in extrasolar planetary atmospheres. This cartoon summarizes the atmospheric mechanisms by which O_2 could form abiotically at high abundance in a planetary atmosphere. The extreme left panel is Earth, the four panels to the right show the different mechanisms and their observational discriminants. Circled molecules, if detected, would help reveal a false-positive mechanism. Failure to detect the "forbidden" molecules in the bottom shaded bar would also help reveal the false-positive mechanism. For example, on a habitable CO_2-rich planet orbiting an M dwarf (second panel from right), the presence of CO and CO_2, and the absence of CH_4, is a strong indicator for a photochemical source of O_2 from the photolysis of CO_2. SOURCE: Hasler/Meadows/Domagal-Goldman.

The other major class of processes that build up abiotic O_2 rely on the photolysis of CO_2 and circumstances that inhibit CO_2 recombination from CO and O_2 (Hu et al. 2012; Tian et al. 2014; Harman et al. 2015; Gao et al. 2015). For photochemical production without atmospheric escape, O_2 abundances as high as 0.2% to 6% are predicted, with higher values corresponding to little or no O_2 sinks in the planetary environment. More realistic modeling of sinks can reduce these estimates by orders of magnitude (e.g., Domagal-Goldman et al. 2014; Harman et al. 2015). Finally, O_3 may be considered a proxy for O_2 in a planetary atmosphere, and large abundances of abiotic O_3 may build up in the massive O_2-rich atmospheres possible after ocean loss (Meadows et al. 2018a), although in these cases large amounts of O_2 will also be present. Domagal-Goldman et al. (2014) were not able to generate large abundances of O_2 from CO_2 photolysis for habitable planets orbiting M-dwarfs, but did produce potentially detectable O_3 column abundance as high as 10% of Earth's modern abundance.

In most cases, the mechanism for abiotic production of O_2 or O_3 leaves a "tell", an impact on the planetary environment that may be detectable. These indications can range from the presence of collision-induced absorption from O_2 molecules that collide more frequently in dense, O_2-rich post-ocean-loss atmospheres (Schwieterman et al. 2016; Meadows et al. 2018a), CO from the photolysis of CO_2 (Schwieterman et al. 2016), lack of water vapor (Gao et al. 2015), lack of collisionally induced absorption from N_2 (Schwieterman et al. 2015), and the absence of reducing gases (Domagal-Goldman et al. 2014). This research has therefore allowed the identification of several observations needed to search for O_2 in a terrestrial planetary atmosphere and to discriminate whether that O_2 is abiotic or biological in origin based on characteristics of the parent star and the planetary environment. By understanding false positive mechanisms and their discriminants, observing strategies are now being developed that incorporate biosignature detection as well as stellar characterization, searches for false positive discriminants and other environmental characteristics that can be used to enhance the interpretation of the biosignature. Comparative planetology can help identify relevant physical and chemical processes in planetary environments that could lead to the generation of a biosignature false positive or contribute to a false negative result. A specific example would be the study of highly irradiated planets (e.g., exo-Venuses) such as GJ 1132b, a terrestrial-density planet that receives the equivalent of 19-times the Earth's solar radiation (Berta-Thompson et al. 2015). GJ 1132b could hold key information to understanding planetary processes that lead to ocean loss or to those that govern the fate of abiotic O_2 generated by photolytic water loss from the planetary atmosphere. Similarly, the influence of jovian planets on terrestrial water inventories, studies of Venus catalytic chemistry (Mills et al. 2006), and the stability of CO_2 photolysis on Mars-like bodies (Gao et al. 2015), all inform understanding of the likelihood and nature of potential false positives.

> **Finding:** Characterizing the atmospheres and incident radiation fluxes for exoplanets of different sizes, compositions, and stellar irradiances is important for confident assessment of planetary habitability and biosignatures because it increases understanding of the physical and chemical processes that lead to false positives and negatives.

The Importance of Environmental Context and Multiple Lines of Evidence

Controversy also enveloped the first reports of microbialites (stromatolites) deposited in rocks of the 3.49 billion-year-old Dresser Formation in the Pilbara Craton of Australia (Walter et al. 1980; Buick et al. 1981). These objects were claimed to represent Earth's oldest signs of life until it was subsequently argued that chemical precipitation alone could explain the phenomena (Grotzinger and Rothman 1996). Further work revealed the compelling contextual association of more diverse, more widespread and better preserved examples of stromatolites in the ~3.45 Ga Strelley Pool Formation (Allwood et al. 2006). The depositional environment was a shallow shoreline where stromatolites have formed throughout most of Earth's history and where they typically form today. Detailed work revealed organic layers that co-varied with stromatolite morphology, and systematic changes in their defining features with water depth

(Allwood et al. 2006). Morphologic diversity correlated with evidence of changes in sedimentation, seafloor mineral precipitation, and microbial mat development (Allwood et al. 2009). More recently, sulfur and carbon isotopic biosignatures (Bontognali et al. 2012; Flannery et al. 2018) and diverse microscopic fossils and carbonaceous objects (Sugitani at al. 2015) have added to the body of independent but complementary lines of evidence for the robustness of the Strelley Pool Formation biosignatures. Further contextual data resulted in the widespread acceptance of the Dresser Formation stromatolites as biosignatures as well (Van Kranendonk et al. 2003, 2008).

As a counter-example, filamentous objects, including haematite tubes and filaments, found in association with 3.8 billion-year-old seafloor hydrothermal vent precipitates have been proposed to be fossil remains of iron-oxidizing bacteria (Dodd et al. 2017). One particular type of bacterium identified in this study, *Leptothrix* sp., is a strictly aerobic iron oxidizing taxon. Not only is there no robust evidence for oxygenic photosynthesis 3.8 billion years ago, numerous geochemical proxies show that the deep ocean seafloor itself remained oxygen free until at least the Neoproterozoic (Lyons et al. 2014). Full ventilation was, perhaps, an even more recent phenomenon (Reinhard et al. 2013; Stolper and Keller 2018). Thus, the context of the putative fossil biosignature seems incompatible with the physiology of iron-oxidizing bacteria.

Modeling cross-comparisons and multiple lines of evidence are also extremely valuable to produce a more robust prediction for the likelihood of abiotic production of O_2 as a false positive for the detection of photosynthesis. There have been disagreements in recent literature about when false positives from the photolysis of CO_2 might occur. On the basis of photochemical model calculations, Hu et al. (2012) concluded that CO_2-dominated worlds around sunlike stars might build up oxygen if the outgassing rates of reduced gases are small, but Segura et al., (2007) and Harman et al. (2015) did not find this. Disagreements on the abiotic production of O_2 on CO_2-rich planets orbiting M-dwarfs (Tian et al. 2014; Harman et al. 2015; Domagal-Goldman et al. 2014) have been recently resolved via model cross-comparison. Confidence in the outcomes of models of planetary processes potentially producing false positives or negatives can be greatly enhanced by intercomparison of modeling methods and results. This is especially true as advances are made in identifying mechanisms potentially generating false positives for O_2 and other proposed biosignatures. The intercomparison of models is, for example, a standard practice in the climate modeling community. This work could also extend to 1D and 3D model comparisons to understand spatial distribution and dynamical mixing of photochemical products.

Developing a Comprehensive Framework for Biosignature Interpretation

The last 5 years have brought a rapid evolution in understanding the complexity of biosignature interpretation and an impetus for the design of more comprehensive search techniques and more rigorous standards of proof. Biosignatures, rather than isolated, specific phenomena, are now understood to occur in an environmental context in which geological, atmospheric, and stellar processes and interactions, along with the evolution of the environment, may work to enhance, suppress, or mimic biosignatures. Consequently, the interpretation of the significance of the potential biosignature, in addition to its measurement, is the most important process in life detection.

Steps towards engaging the community in the development of several systematic, progressively comprehensive frameworks are being undertaken. One example is the NASA Ladder of Life Detection (Neveu et al. 2018), which provides a community accessible spreadsheet to identify and discuss proposed in situ biosignatures and their potential false negatives and positives. The ultimate goal of the Ladder of Life Detection is to help identify sets of measurements that together discriminate between a biotic or abiotic origin for potential biosignatures, with high statistical significance. For example, formalisms such as ROC (receiver-operator characteristic) curves can provide a quantitative foundation for the selection of which biosignatures to pursue in a particular setting. A ROC curve is a classification model that is used to set threshold values for predicting outcomes, taking into account the probabilities of both false positives and false negatives. First applied to the detection of radar signals, this approach is now widely used in areas as diverse as clinical diagnostics, weather prediction, and machine learning. Such formalisms bring mathematical rigor to the search for life, but they require support by test measurements made under simulated operational conditions. It will be the task of the scientific community to make the relevant measurements of true and false biosignatures and to determine how these measurements can be combined to provide a coherent predictive model.

> **Recommendation: NASA should direct the community's focus to address important gaps in understanding the breadth, probability, and distinguishing environmental contexts of abiotic phenomena that mimic biosignatures.**

An analogous activity has been undertaken for exoplanet biosignatures, mediated by the community discussions at the 2016 NExSS Exoplanet Biosignatures Workshop. The template for this framework has been developed for O_2, taking into account false negatives, and their impact on target selection; and false positives, and the observing strategy required to discriminate them from true biosignatures (Meadows et al. 2018b). Generalizing this template, Catling et al., (2018) presented a framework for biosignature assessment that allows the detection of life to be expressed as a probability. This framework uses Exo-Earth System models to simulate potential biosignature observations with are then compared with actual observations to determine the Bayesian likelihood of those data occurring for scenarios with and without life (false positives). The Bayesian methodology provides a medium to quantitatively define conditional probabilities and confidence levels for biosignature detection. However, it also requires interdisciplinary laboratory, field and theoretical work to place constraints on relevant likelihoods, including those emerging from stellar and planetary context, and the contingencies of evolutionary history. The Bayesian framework can also guide search strategies, including determining observational wavelengths or deciding between targeted searches or larger, lower resolution surveys, while providing a flexible framework that is not constrained to specific metabolisms or biosignatures (Walker et al. 2018).

> **Recommendation: NASA should support the community in developing a comprehensive framework for assessment—including the potential for abiosignatures, false positives, and false negatives—to guide testing and evaluation of in situ and remote biosignatures.**

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5

Evolution in the Technology and Programmatic Landscape

TECHNOLOGY FOR SEARCHING FOR LIFE ON NEARBY EXOPLANETS

NASA's Kepler mission revolutionized the field of exoplanet astrobiology by proving that rocky, potentially habitable worlds are commonplace in the Milky Way galaxy as first prioritized by the 2001 Astronomy and Astrophysics Decadal Survey (NRC 2001). The path forward is to determine which of these worlds might be not only habitable, but perhaps even inhabited. Fortunately, even before the stunning results from Kepler, NASA and its community advisors prioritized the search for habitable, inhabited exoplanets. This has resulted in several space telescopes currently in operation, development, or planning. Ground-based astronomers and their observatory advisory bodies have similarly been preparing in anticipation of this new era of exoplanet astrobiology to make use of telescopes already in operation or undergoing upgrades, development, or planning over the next decade. Together, these telescopes continue the hunt for a convincing biosignature.

Although the Kepler mission finished its extended phase in 2017, and the follow-on Kepler K2 mission will conclude this year, NASA's follow-on space transit photometry telescope—the Transiting Exoplanet Survey Satellite (TESS)—launched successfully on April 18, 2018. During its two-year prime mission, TESS is expected to discover at least 50 small exoplanets (i.e., Neptune-size or smaller) orbiting in the habitable zones of nearby bright M-dwarf stars (e.g., Ricker et al. 2015). Ground-based follow-on programs using high-precision Doppler spectrometers will be employed to determine the masses of these exoplanets with the goal of assessing if the targets are truly "Earth-like".

In large part, TESS is intended to be a finder telescope for NASA's next flagship telescope, the 6.5 m James Webb Space Telescope (JWST). JWST will use the approach pioneered by the Spitzer Space Telescope to study the atmospheres of exoplanets through precise measurements made during both transits and occultations, when delicate subtractions of the combined stellar and planetary starlight can be employed to separate the exoplanet's atmospheric features from those of the host star. However, this approach only works for transiting planets, such as the seven transiting planets in the TRAPPIST-1 system and the exoEarths expected to be found by TESS. While the launch date has been delayed multiple times and is currently expected to be no earlier than late-March, 2021, JWST is anticipated to provide unprecedented sensitivity for imaging and spectroscopy in the infrared.

For those planets that do not transit their host stars from the observer's perspective, space-based telescopic discovery and characterization requires either an internal coronagraph or an external starshade, or, ideally, both. This is necessary to attain the high contrast needed to directly image non-transiting exoplanets. NASA's Wide Field Infrared Survey Telescope (WFIRST), slated for launch in 2025, is baselined to carry a coronagraph that will test and prove the technology needed for future space telescopes capable of the direct imaging of Earth-like planets. The last several years have seen substantial investment in the WFIRST coronagraph. These investments have yielded a coronagraph able to detect exoplanets that are approximately 10 million times fainter than their host stars, ins pite of the non-ideal obscured pupil design of the WFIRST optical system. Coronagraphs designed for a more ideal, un-obscured pupil are expected to be able to achieve considerably better performance.

Parallel to further development of internal coronagraph technology, NASA is developing the technology needed to build and deploy large (30-50 m) starshades. Starshades fly in formation with the telescope and are suitable for operation with WFIRST or other future space telescope. Decisions regarding the prioritization of these technologies will be made by the Astronomy and Astrophysics 2020 Decadal Survey (Astro 2020). In support of Astro 2020, NASA has been supporting several planning studies for large (4-12 m) optical, space-based observatories that will offer technological options to fly as the next flagship mission following WFIRST.

The main challenge for exoplanet spectroscopy is starlight suppression. The light from stars can be 10 billion times brighter than that of a rocky planet in its habitable zone. Starlight suppression technologies, such as coronagraphs and starshades, and nulling interferometers can be used to suppress the light from an exoplanet's host star (NASA 2018). Transmission spectroscopy, high-resolution Doppler spectroscopy, and phase-curve measurements have been used to determine the composition of exoplanet's atmospheres (e.g., Brogi et al. 2013; Birkby et al. 2013; de Kok et al. 2013; Brogi et al. 2014). Spectroscopy and photometric measurements using the combined line from an exoplanet and its host star are fundamentally limited by stellar photon noise which limits the potential for characterization of habitable planets. Thanks to starlight suppression techniques, the planet's light can be separated from most of the starlight, providing measurements with a significantly better signal-to-noise ration

Recommendation: NASA should implement high-contrast starlight suppression technologies in near-term space- and ground-based direct imaging missions.

In addition to the anticipated launch of a direct-imaging space telescope, a new generation of 30m class ground-based giant segmented mirror telescopes (GSMTs) will be deployed in the 2020s. These telescopes increase collecting area per telescope by an order of magnitude over the current 8-10 m diameter telescopes. The three-fold increase in angular resolution and improved sensitivity, combined with advances in supporting technologies such as adaptive optics (to mitigate image degradation caused by Earth's turbulent atmosphere), detectors, computing power, and machine learning will provide new measurement opportunities for exoplanet observations. Two U.S. teams, the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT), plan on searching for exoplanets with their first light spectrographic instruments. The European Extremely Large Telescope (E-ELT) has a similar focus on detecting and characterizing nearby exoplanet systems.

In summary, these space- and ground-based telescopes offer significant new opportunities for studying exoplanets. Using transit spectroscopy, large observatories such as JWST and the GSMTs will have the sensitivity to characterize the atmospheres of the nearest transiting habitable planets orbiting M-type stars. Using direct imaging of reflected light from the host star, ground-based GSMTs will provide the angular resolution and sensitivity to image reflected light habitable planets orbiting nearby low-mass main sequence stars of M- and possibly K-types (see, for example, Kopparapu et al., 2018, for a means to estimate the number of exoplanets expected to be seen using direct-imaging missions). Spectroscopy in the near-IR will reveal atmosphere compositions, which could yield molecules associated with biosignatures, such as atmospheric water, oxygen, methane, nitrous oxide, carbon monoxide, and carbon dioxide. High-resolution spectroscopy observations will need to calibrate their measurements against Earth's atmosphere perturbations and will reveal valuable exoplanet dynamic features (e.g., planet orbital motion and rotation). Space-based optical telescopes, free of atmospheric turbulence, will reach the contrast level required to image the reflected light of habitable planets around Sun-like (types F-, G-, K-) stars. Direct imaging of the thermal emission of Earth-like planets orbiting the nearest A-, F-, and G-type stars will be observable with GSMTs in the mid-IR (~7-13 µm) thanks to the exoplanets' thermal emission, where the contrast ratio between the planet and the star is typically a thousand times better than at optical wavelengths.

BOX 5.1
Nucleic Acid Detection

There are many established methods for the in situ detection of nucleic acids. Most of these require a prior amplification step, usually by some form of the polymerase chain reaction (PCR). PCR amplification employs either fixed- or random-sequence primers that are complementary to the sequence to be amplified. Larger quantities of DNA or RNA can also be detected directly through hybridization methods, which require prior knowledge of the sequence being detected. More recently, technologies have been devised for sequencing individual nucleic acid molecules without a prior amplification step or prior knowledge of the sequence being detected (Eid et al. 2009; Jain et al. 2016).

Among the intriguing new technologies with regard to potential applications in solar system exploration is nanopore sequencing, as exemplified by, but not limited to, the MinION device from Oxford Nanopore Technologies (Figure 5.1.1). The MinION is a USB-powered portable device containing a flow cell with 512 individually addressable protein nanopores. It has been operated successfully on the International Space Station (Castro-Wallace et al. 2017). However, it has not been subject to the stressing conditions found in extraterrestrial environments. Searching for nucleic acids and other informational biopolymers in a non-terrestrial settings requires consideration of not just the sequencing device, but also the systems engineering needed for sample acquisition and processing.

The MinION device detects changes in ionic current as individual subunits of the DNA polymer are drawn through the nanopore. It can detect both standard and modified bases and, in principle, could be used to detect individual subunits within other heteropolymers. However, like all existing sequencing technologies, nanopore sequencing requires sample processing steps that are custom-tailored to DNA molecules. These steps include the enzymatic ligation of an adapter DNA to the end of the sample DNA, which enables capture of an enzyme to ensure unidirectional displacement of the DNA through the nanopore. Although there have been proof-of-principle experiments suggesting that polypeptides could be sequenced using nanopore technology (Nivala et al. 2013), these methods have not yet been reduced to practice and are not compatible with existing commercial devices.

FIGURE 5.1.1 MinION USB-powered device for single-molecule DNA sequencing. SOURCE: Reproduced with permission © Oxford Nanopore Technologies.

> **Finding:** Technologies for spectroscopic measurements and high-contrast direct imaging have advanced rapidly in the last decade, making possible the remote characterization of the atmospheres of nearby rocky exoplanets and enabling the search for potential biosignatures within the next two decades.

Numerous challenges remain, however. Exoplanet observation techniques need to be able to extract small signals from the noise. While large ground and space telescopes will have the sensitivity and angular resolution to image and characterize exoplanets, the measurements remain challenging, especially for ground-based telescopes that have to overcome the scattering of starlight due to turbulence, absorption and emission of gases in Earth's atmosphere. The interpretation of the measurements will also be challenging. Better understanding of biotic and abiotic processes that could influence atmospheric signatures, especially for planets orbiting M-type stars, is required. Transit spectroscopy, direct imaging, Doppler spectroscopy, and astrometry will provide a rich dataset, but with a small overlap in targets. The results will likely suffer from small-number statistics. Combining this information to infer both statistical distributions and individual exoplanet properties will be very challenging.

TECHNOLOGY FOR SAMPLE-BASED LIFE DETECTION

Instrument technologies that can contribute to in situ life detection in samples have developed rapidly in the past decade as the result in particular of investments made by companies in the biomedicine, food security, and defense sectors. Comparatively modest investments might be sufficient to transform such instruments, including miniaturized mass spectrometers and DNA sequencers (e.g., Box 5.1) for rapid sample analyses, into capable spacecraft hardware able to address astrobiological mission goals and/or ensure compliance with appropriate planetary protection requirements (Box 6.2). Further, the exceptional computational capability developed in the past decade allows rapid analyses of these samples onboard a spacecraft. Together, these advances increasingly facilitate in situ sample analysis that previously would require sample return to Earth.

Raman microspectroscopy would be well suited for in situ detection of organic materials and characterization of associated minerals, including hydrated phases (e.g., Wang et al. 2006). While fluorescence may hinder the identification of some minerals, Raman spectroscopy has the advantages of not requiring a great deal of sample preparation and, as it is non-destructive, allowing further analyses to be done on the same location in the sample.

Importantly, Raman spectroscopy is also a powerful tool for identifying organic matter indigenous to the metamorphosed rocks and not derived from post-metamorphic processes. Raman spectroscopy provides structural information about the organization of the aromatic skeleton of graphitic carbons (Bernard et al. 2010) which evolves systematically with increasing metamorphic grade (e.g., graphitization; Beyssac and Lazzeri 2012). A geothermometer has been calibrated based on Raman spectral characteristics of carbonaceous materials by Beyssac et al. 2002). This technique has been recently widely and successfully used to estimate the peak temperature experienced by carbonaceous materials from various lithologies and ages, including early Archean rocks (Ueno et al. 2004; Wacey et al. 2011; Sugitani et al. 2013, 2015; Morag et al. 2016; Hickman-Lewis et al. 2016; Flannery et al. 2018). For further characterization of the organic materials, synchrotron-based scanning transmission X-ray microscopy (STXM) allows microscopic observations with chemical sensitivity, i.e., in situ mapping of organics within rocks at a 15-nm spatial resolution, and spectroscopic measurements of X-ray absorption that offer a precise estimation of the nitrogen-to-carbon atomic ratio of organics (Alleon et al. 2015) as well as key information about carbon and nitrogen speciation at the submicrometer scale (Alleon et al. 2016).

The field of paleogenomics holds significant promise for understanding the connections between life and the environment. Growing understanding of the last universal common ancestor and ancient genetic information will allow increasingly sophisticated tests of successful organismal and community evolutionary strategies in the context of their environments, thus becoming not just tools to study life's innovations, but its record of environment change, as well. At the same time, synthetic biological techniques may be adapted to allow astrobiologists to reverse-engineer genes to discover their ancient function, thereby revealing their impact on the environment or their environment's impact on them.

For extant life detection, the challenge is the absence of a single, mature flight-ready instrument capable of making in situ measurements of elemental, mineralogical, and organic composition. Of particular importance is the ability to detect long-chain informational polymers associated with replicating genetic systems. On Earth, the genomic polymers are RNA and DNA, which encode functional polymers based on RNA, proteins, and oligosaccharides. While these polymers may take a different form on other planets, informational polymers in general can be regarded as a signature of life. Information polymers are uniquely important because even surprisingly complex materials such as amino acids, sugars, and nucleobases can be produced by abiotic processes and have been observed in meteorites without any evidence for biosynthesis. One further requirement for such instruments would be the ability to analyze sample materials non-destructively. The destructive techniques commonly employed in current in situ analyses are excellent for determining low-level elemental and molecular composition of ingested materials, but they often lose the measurement context and create new compounds during sample processing. Although techniques for standoff measurements are relatively mature, they frequently return non-unique information about organics.

> **Finding:** The commercial availability of compact, low-power, RNA and DNA sequencing devices could contribute significantly to the robustness of the current portfolio of life detection technologies.
>
> **Finding:** Current technology for DNA amplification and sequencing may be useful for in situ detection of terrestrial contamination and lifeforms that are closely related to terran life, but at present, they are not sufficiently agnostic to the subunit composition of an informational heteropolymer.

On Earth, one key issue for in situ biosignature research, particularly with respect to fossil biosignatures, is the mineral-scale context of the purported biosignatures. This is amply demonstrated by the approach developed for Mars 2020 (Hays et al. 2017), for which the Planetary Instrument for X-Ray Lithochemistry (PIXL; Allwood et al. 2016) and the Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC; Beegle et al. 2016) are able to co-locate carbon on a mineral scale. In situ compositional (mineral, carbon) and elemental analyses in combination with optical microscopy with provides essential context for gas chromatography-mass spectrometry and laser desorption-mass spectrometry destructive analysis of organics. Thus, a key emerging technology necessary for astrobiological missions is optical microscopy. Microscopy can be used for the detection of both extant and extinct life, although the signatures of extinct (fossil) life can be enigmatic. Further, microscopy observations need to be coupled with other lines evidence of biogenicity, such as environmental context, chemical and isotopic composition, and informational polymers that are suggestive of biological origin (Westall et al. 2015a,b). Transmitted light microscopy is particularly useful, however, it requires making sections of rock thin enough (several tens of microns thick) to allow the transmission of light and observation by a microscope. Normally, but not always (depending upon the nature of the material to be sectioned), water is used during the sawing process. New methods are being developed to prepare thin sections without the use of water and with minimal energy requirements for utilization not only in in situ space missions but also in terrestrial laboratories, such as extraterrestrial sample curation facilities and others (Foucher et al. 2017). Such an instrument can be coupled with Raman and laser-induced breakdown spectroscopy (LIBS) to provide organic and elemental analysis. The addition of an IR spectrometer could also be envisaged. This kind of instrument would provide essential contextual information from drill samples that are also used for organic biosignature organic analysis by GCMS and LDMS, as on the ExoMars 2020 rover (Goesmann et al. 2017) (Vago et al. 2017).

Fortunately, recent advances have demonstrated that high resolution microscopes are increasingly able to be adapted to planetary landers or rovers. For example, sub-micrometer resolution optical microscopes are now capable of autonomous operation (Nadeau et al. 2018). Holographic microscopes are capable of imaging relative large volumes and do not require focusing, both of which are important for space flight instruments. In addition, they are capable of detecting transparent objects without the need for staining. An addition promising method employed in biological studies on Earth uses fluorescent labeling with dyes followed by high-resolution light microscopic imaging (Nadeau et al. 2018). Commonly-used dyes produce low background fluorescence and signals that increase upon binding to chemical targets, facilitating their detection. Fluorescent imaging also increases effective spatial resolution by allowing microbial features that are unresolved, such as flagella, to be observed. Dyes, however, can produce ambiguous results because they may also bind to mineral particles, organics, and even complex materials such as amino acids, sugars, and nucleobases that can be produced by abiotic processes. Microfluidic platforms provide a means of moving samples between detection systems and can operate in combination with fluorescence microscopy to search for microorganisms and to study their response to different agents (Ricco et al. 2018). Advancements in low-mass and robust optical systems, such as single focal-plane systems, in the ability to image samples in low light, and in the ability to image the full volume of these samples, are evolving technologies.

> **Finding:** New technologies for microscale and nanoscale analyses combining optical microscopy, Raman spectroscopy, laser-induced breakdown spectroscopy, infrared, and other interrogatory methods offer promise for advancing the detection of and confidence in microscale biosignatures.

The interpretation of biogenicity needs to be based on observation of a complementary suite of biosignatures. Technologies and techniques for the characterization of organic materials are most useful if able to detect not only informational polymers, which are currently known to be unique to life, but also simple polycyclic aromatic hydrocarbons and shorter chained molecules. These materials form the backbone of biochemistry and, even in the absence of biologic processes, may contain contextual information about the environment. Microstructures (fossil or extant) and even motility, detectable by advanced microscopic techniques, may provide lines of direct evidence for life. Traditional lander and rover payloads further characterize the context in which possible biosignatures are discovered. These analyses together provide the multiple lines of evidence needed to create a convincing case for a purported biosignature. Notably, just as would be the case on Earth, these analyses will require a full suite of laboratory instruments.

> **Finding:** In situ detection of life is best advanced by integrated suites of instruments or single instruments that permit multiple analytical techniques, including non-destructive approaches, to be applied to the same materials.

> **Finding:** It is important that science requirements drive sample handling technologies—including ingestion and non-destructive sample preparation and analysis—rather than off-the-shelf engineering solutions or ease of implementation.

PROGRAMMATIC CHALLENGES AND OPPORTUNITIES

Challenges to a focused portfolio of life detection technologies also stem from programmatic elements. Such elements identified by the committee include a risk-averse environment that in some cases may stifle the selection of high science risk but high payoff instrumentation and missions, relaxed specification for proposer-derived success criteria, and the need for innovative instruments and complex sample handling systems. Perhaps even more importantly, the planetary exploration program has remained deeply rooted in the non-biological sciences dating back to the Apollo sample analysis program and the early Mariner flyby missions to Mars and Mercury. Long-standing questions about the possibility of life on Mars led to the biology experiments on the Viking landers in the latter half of the 1970s, but planetary exploration thereafter returned to its geologic roots. The NASA Origins Program of the late 1990s and early 2000s, stimulated in part by the possibility of evidence for life in a martian meteorite, brought questions of life back to the center stage of planetary exploration. In the years since, astrobiology has developed, with strong NASA support, into a vibrant interdisciplinary field characterized by integrative, systems-level thinking about how a planet transforms from non-living to living and how life and a planet co-evolve.

For the past two decades, questions focused on planets from geological and astrobiological perspectives have largely overlapped in instrument and measurement requirements. Planning, implementation, and operations of planetary exploration missions with astrobiological objectives have tended to be more strongly defined by geological perspectives than by astrobiology-focused strategies. Deepening insights appear to be leading toward some divergence, however. For example, biosignature detection increasingly requires specialized instrumentation such as macro- to micro-scale imaging, spectral imaging, mass spectrometry and, potentially, nucleotide sequencing technologies. Further, operational requirements for astrobiology-focused investigations may be better achieved by a grid-based approach, in which an area is divided into individual nodes for surveying, rather than by traditional geological traverses along a planned path. For example, the grid approach was key to the Curiosity Rover discovery of an ancient habitable environment at Yellowknife Bay in Gale Crater. The opportunity to apply this approach, however, resulted mainly from mission operational constraints that prevented beginning the planned geological traverse shortly after landing. It has thus become imperative to more fully integrate astrobiological thinking and objectives into mission planning, implementation, and operations.

Current mission selection processes emphasize a need for low risk in technological readiness level (TRL), which is tied to spacecraft engineering as opposed to science. Current NASA instrument evaluation and selection policies tend to favor low technology risk, which in some cases adversely impacts scientific payoff. This inhibits development and selection of potentially game-changing life detection technologies, for example. For example, currently, a high science risk activity may be defined as recognizing carbon, which is a proven engineering capability. Detecting carbon of any type in situ (as recently demonstrated for Mars by Eigenbrode et al. 2018)–i.e., directly in regolith or in rocks–is extremely difficult. Nevertheless, detecting and characterizing carbon has enormous scientific potential because it could unambiguously confirm one or more of the following:

1. The presence of one of the main ingredients of life on an extraterrestrial body, and
2. The presence of biogenic carbon with particular compositional and structural patterns as compared to abiogenic carbon.

At the same time, instruments suitable for environments in which life detection activities may be relevant – such as Europa, Titan, or astrobiological targets on Mars – are rare. The lunar, asteroid, and low-Earth orbit environments are significantly different from what in situ life detection instruments would encounter on rocky or icy planets in the solar system, and there is lower science need for such techniques to be developed for these more easily accessible environments. There is renewed need for development of instruments with high science potential even in the face of high development risk.

> **Finding:** Current NASA instrument evaluation and selection policies favor low technology risk with, in some cases, potentially low scientific payoff. This inhibits development and selection of potentially game-changing life detection technologies.
>
> **Finding:** Planning, implementation, and operations of planetary exploration missions with astrobiological objectives have tended to be more strongly defined by geological perspectives than by astrobiology-focused strategies.
>
> **Recommendation: To advance the search for life in the universe, NASA should accelerate the development and validation in relevant environments, of mission-ready, life detection technologies. In addition, it should integrate astrobiological expertise in all mission stages—from inception and conceptualization, to planning, to development, and to operations.**

In the current paradigm, mission teams and instrument providers define their own instrument success criteria. As a result, a wide range of instruments has claimed to address questions of habitability and further life detection goals on the basis of the possibility of making microscopic observations and detecting and analyzing carbon and carbon-containing molecules. In some cases, this allows instruments with low science potential for astrobiology science community goals to be selected for flight on the basis of high heritage. In this way, the current instrument selection process can be biased against complex techniques with high science potential. Moreover, when proposers define their own samples and data against which the instruments are tested, it is left to the panel, who are unlikely to be life detection experts, to decide for themselves whether a test is relevant or not. The creation of standards relevant to specific conditions, context, and instrument detection level will aid the detection of biosignatures and life itself.

> **Finding:** Because of possible ambiguity in proposer-defined instrument success criteria, there is inherent risk in using these to propose, to evaluate, and to select instruments designed to detect biosignatures, rather than using observation and measurement validation standards established by community consensus.

Many of the most challenging goals with regard to habitability and life detection cannot be achieved with a single instrument. Therefore, missions that select instruments as stand-alone or that do not allow cross-instrument requirements or project-wide level 1 requirements impact science, can increase risk, and miss opportunities. In fact, inter-instrument tests of a mission payload are essential to demonstrate the complementarity of the payload and how the best observations from each instrument can be linked to provide the full picture (e.g., Bost et al. 2015). In the field of astrobiology, flagship missions are particularly at risk of the perception of diminished science returns. These missions require interdisciplinarity to answer systems-level questions, however, instruments are selected independently. Therefore, mission implementation can be a risk to life detection science. The Europa Clipper mission is an example of a mission in which instruments depend on each other, in which the main mission driver, habitability, cannot be achieved with a single instrument, and in which the project team and project science group have played a crucial role in allowing for cross-instrument trades and synergy to be planned and executed. This is also the case for the European-Russian ExoMars 2020 mission to search for traces of life (mostly fossil but possibly extant) within the context of the geological environment.

NASA’s Astrobiology program, which includes but is not limited to the NASA Astrobiology Institute, has been admirably forward thinking with regards to community building, fostering interdisciplinary collaboration and cooperation, and facilitating major advances in astrobiology and planetary research. The NASA Astrobiology program has made valuable investments in training, growth and diversification the next generation of astrobiologists through several platforms that target early career scientists, including AbGradCon and FAME Lab. From 2012 through 2016 the NASA Astrobiology Program sponsored FameLab competitions across the United States, to improve and expand the communication skills of early career scientists. During the four years of FameLab USA, 247 early career scientists from a broad array of disciplines and career stages benefited from the FameLab experience. In addition, the Astrobiology Program through the NASA Astrobiology Institute (NAI) has provided numerous channels of support for early career scientists including the Lewis and Clark Fund for Exploration and Field Research in Astrobiology (jointly with the American Philosophical Society); the Early Career Collaboration Fund; summer and winter school opportunities, and conference travel support. Another activity that NASA has sponsored to further interdisciplinary work in this area is a series of workshops on the theme of Comparative Climatology of Terrestrial Planets (CCTP). These workshops have brought together climate scientists from across the globe to discuss progress in understanding the climates of rocky planets beyond, but still including, the Earth.

Since 2015, the Astrobiology program has also implemented a new cross-divisional research coordination network, the Nexus for Exoplanet System Science (NExSS) as a large-scale experiment in managing and catalyzing exoplanetary science that integrates the astronomical, terrestrial, planetary and heliophysical sciences. The NExSS research coordination network provides the communications and community organization to connect and leverage research funded by several research and analysis (R&A)

competitions across cooperating NASA divisions, breaking down interdisciplinary and interdivisional barriers, and integrating the larger scientific community into its activities. NExSS led activities include the Upstairs-Downstairs Workshop (2016) on the impact of terrestrial planet interiors on planetary atmospheric and surface conditions, which was jointly supported by the NAI and National Science Foundation (NSF); the Exoplanet Biosignatures Workshop (2016), which produced 6 community scientific publications that greatly advanced our understanding of the significance of false positives and agnostic biosignatures, as well as developing the comprehensive framework for biosignature assessment (Kiang et al. 2018; Schwieterman et al. 2018; Meadows et al. 2018b; Catling et al. 2018; Walker et al. 2018; Fujii et al. 2018); and the Habitable Worlds Conference (2017), which had strong participation from Earth scientists, planetary scientists and heliophysicists, in addition to astronomers and exoplanet scientists. A NExSS-led community group developed a Laboratory Astrophysics Gap List of needed laboratory studies to be able to interpret exoplanet spectra (Fortney et al. 2016), and contributed numerous white papers to this NASEM study and the parallel exoplanets study. NExSS PIs and their collaborators also contributed to plans for utilization of current space telescopes by bringing together the US and international research communities (in almost equal numbers) to win a proposal for exoplanet characterization for JWST Early Release Science. These proposals will provide the critical initial characterization of the telescope's performance for exoplanets, as a first step towards habitable zone planet characterization and biosignature searches with JWST. It is also noteworthy that individual cross-divisional collaborations to study exoplanet environments are being fostered at NASA centers: for example, the Sellers Exoplanet Environments Collaboration at NASA's Goddard Space Flight Center.[1]

One of the major goals of the Astrobiology program is to advance astrobiology on NASA missions, and while the participation of astrobiologists has enabled significant progress in understanding how JWST and the future Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) and Habitable Exoplanet Imaging Mission (HabEx) telescope concepts could be used to search for signs of habitability and life on exoplanets, few solar system missions currently carry astrobiology instrumentation. While the discussion is actively changing in the planetary science community–e.g., the resurgence of interest in the ocean worlds is driven by the interest in search for life–it is essential that NASA Astrobiology continue to find ways to enable cutting edge thinking, especially that which advances exploration objectives.

> **Finding:** Cross-divisional collaborations promoted by NASA's Astrobiology Program between Earth science, astronomy, heliophysics, and planetary science have begun the task of breaking down disciplinary entrenchments and are helping the astrobiology and exoplanet communities reach their full potential.

New launch capabilities will also provide lower cost access to Mars and beyond. Game-changing innovations in small platforms such CubeSats, exoplanetary exploration drones and ambitious, privately funded initiatives such as the laser-powered starshot project are opening new opportunities for space exploration. Such advances are relevant for solar system exploration, which has been severely limited by decade-long intervals between consecutive missions combined with limited instrument flexibility requiring incremental approaches such that mission instrumentation payloads are largely informed by results of previous missions.

DEVELOPMENTS IN DRILLING TECHNOLOGY AND SAMPLE HANDLING

Access to and sampling of the subsurface is an important strategy in the search for extant life, or for signatures of past life on planetary bodies (e.g., Skelley et al. 2005). For both rocky planets and ocean worlds, when harsh conditions at their surfaces render the surface environments inhospitable, the

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[1] For more about the Sellers Exoplanet Environments Collaboration see https://science.gsfc.nasa.gov/600/seec/index.html.

subsurface provides a potential refuge, where liquid water, nutrients and chemical energy may be available and preservation of habitat or biosignatures may be more favorable.

The MER and Curiosity rovers made important discoveries using a grinder and scoop that allowed some investigation of the shallow subsurface of Mars, on a mm-cm scale at least. The discovery of the transition from gray soils to reddish material presumably representing the transition from a reducing to oxidizing zone was a major discovery (Figure 5.1). Following up this on Mars by accessing below the limits at which organics are seriously degraded by radiation, to 2m as planned by ExoMars (Vago et al. 2017), and beyond 2m, has focused attention on development of drilling capabilities. Similarly, the mission concepts for ocean worlds have focused thinking on more specialized drilling tools since icy crust at the low temperature surfaces is extremely hard.

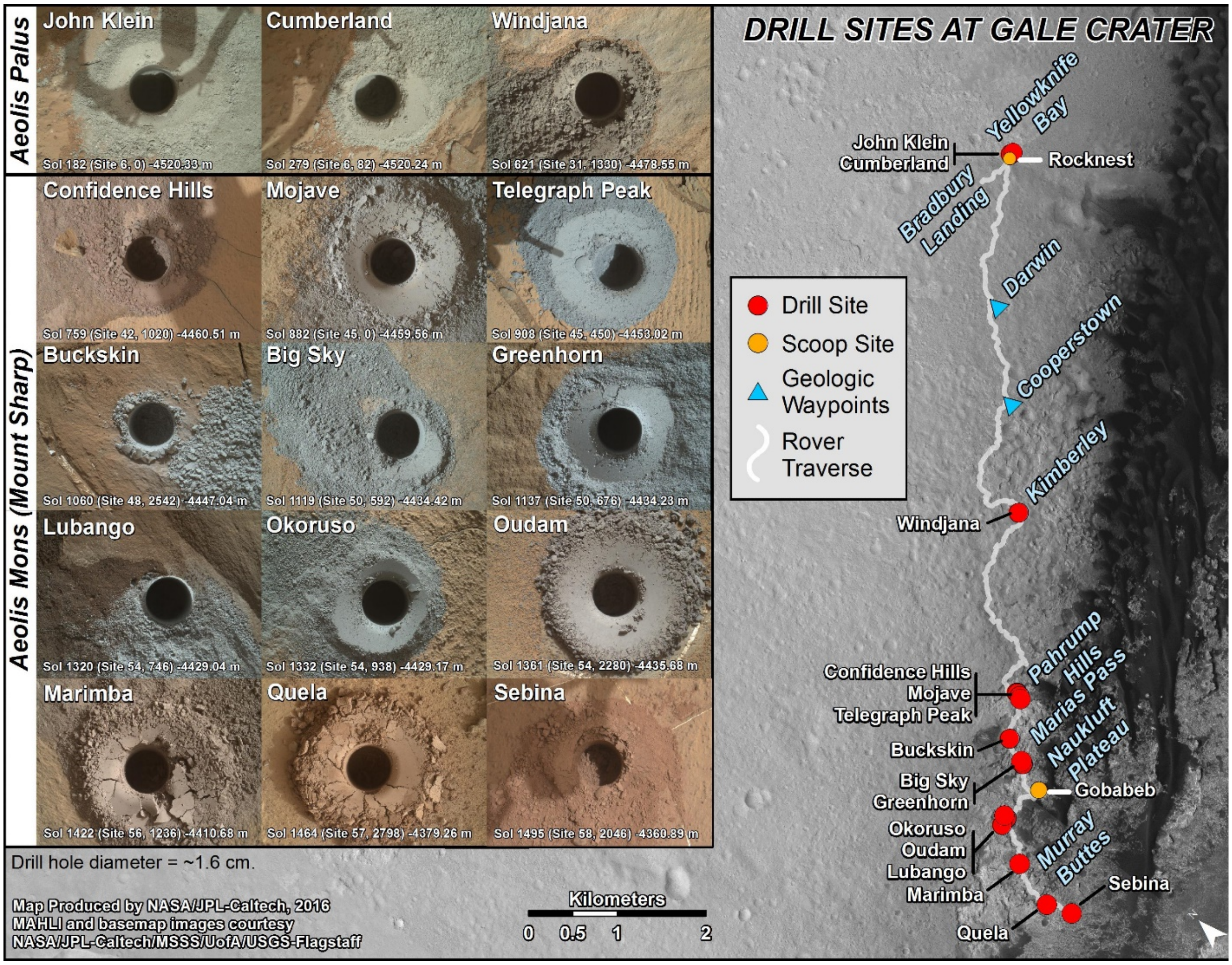

FIGURE 5.1 The locations where NASA's Curiosity rover collected its first 19 rock or regolith samples for analysis are indicated on this map of Gale crater. Also shown are images of the drilled holes where 15 rock-powder samples were acquired. The four remaining samples where of regolith collected at the Rocknest and Gobabeb sites. The diameter of each drill hole is about 1.6 centimeters. The images used here are raw color, as recorded by the rover's Mars Hand Lens Imager (MAHLI) camera. Note the differences in the color of the material sampled at each of the sites drilled. North is toward upper left corner and this map of the rover's traverse is based upon images obtained by the High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter. SOURCE: Ashwin Vasavada. SOURCE: NASA/JPLCaltech/MSSS.

Typical drills move forward into the subsurface due to the forces of large weights or via anchoring (Zacny et al. 2008; Okon 2010). This is a challenge in low gravity environments because high mass systems are not desirable for extraterrestrial exploration. Biologically inspired solutions composed of toothed elements, such as Dual Reciprocating Drilling (DRD) systems, show promising results for drilling in certain types of planetary surfaces (Gao et al. 2007). The DRD technology consists of a pair of half cylindrical teethed elements opposing each other that reciprocate with linear motion, reducing the forces necessary for inserting the drill into the ground.

Drilling technologies that do not require large overhead forces (referred to as the weight on bit) will enable the search for in situ biosignatures in planetary subsurfaces. These technologies will need to be able to collect samples without altering their composition significantly (e.g., Kereszturi 2016). In particular, excessive heating is likely to cause chemical alteration and the release of volatiles, as demonstrated by the drill on the ExoMars 2020 rover (Vago et al. 2017). Furthermore, processing of subsurface samples obtained from drill cores needs to avoid significant physical and chemical alteration, including cementation and cross-contamination, before distribution to astrobiology science instruments (e.g., Richter et al. 2015). Significant progress has been made on these areas in recent years via ExoMars (Vago et al. 2017), and the Mars2020 sample caching programs (Mustard et al. 2013), while pilot programs to advance ice drilling capabilities have been conducted in analogue environments, such as Antarctica (Talalay 2014), and the Arctic (Hansen 2018). In the latter cases, different types of drilling regimes are used, for instance, dry drilling or wet drilling using antifreeze agents, such as ethylene glycol or hot water. Recent years have seen better understanding of the challenges involved in drilling to retrieve uncontaminated biological samples on Earth, both in the deep crustal subsurface (e.g., Wilkins et al. 2014) or, for instance, into various Antarctic lakes (Siegert et al. 2016). Recent technological advances in automation and remote drilling, miniaturization, data processing, sensor and imaging technology are also significant enabling technology supportive of subsurface investigations and sample acquisition (Stamenkovic et al. 2018).

BIG DATA ANALYSIS TECHNIQUES

Artificial intelligence (AI), or the ability of a computer to conduct inferences and other activities autonomously without human intervention, is a rapidly evolving computational science with an increasing breadth of applications. This field has spawned a range of computer algorithms, such as machine learning, that are capable of adaptively analyzing large data sets (assuming that they have been maintained in usable formats) with specific well-defined objectives (e.g., face and speech recognition). In particular, deep learning is a specific mode of machine learning that makes use of neural networks that have multiple layers of tunable parameters and learning objectives engineered to a specific purpose. Machine learning with deep-learning is expeditiously progressing in both the commercial and public sectors. In the last few years, it has begun to be incorporated in astrobiology studies. For instance, the use of machine learning with exoplanet detection has been used with Kepler data (McCauliff et al. 2015; Thompson et al. 2015; Shallue and Vanderberg 2018), exoplanet detection routines with direct imaging data (Gomez-Gonzales et al. 2016), as well as in upcoming missions like TESS (Pearson et al. 2018). In this solar system, analysis of space- and ground-based images of Mars is being advanced with machine learning routines (Rothrock et al. 2016; Wagstaff et al. 2017). Life detection approaches for DNA sequencers for base labeling are also using deep learning techniques (e.g., Boza et al. 2017). Similarly, Bayesian frameworks in computational sciences are anticipating applications in comparative planetology and exoplanet biosignatures (e.g., Walker et al. 2017). Although machine learning analysis techniques need to be tailored and adapted for each application, there is a growing alignment between astrobiology goals and the commercial sectors that are currently heavily investing in AI development.

Finding: Rapid progress in the development of artificial intelligence machine learning algorithms has the potential to improve analysis of the large, complex data sets increasingly common to astrobiology.

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The Search for Life in the Coming Decades

Taking the 2015 Astrobiology Strategy as its starting point and building on that foundation, Chapters 2, 3, 4, and 5 of this report has emphasized additional insights from recent advances in the field, both intellectual (e.g., conceptual insights and frameworks, modelling), empirical (e.g., key discoveries and observations, technology development and novel technologies) and programmatic. Arising from those updates, in this chapter we identify the most promising key research goals and questions in the field of the search for signs of life in which progress is likely in the next 20 years, and discuss pathways by which of the key goals can be addressed by U.S. and international space missions and ground telescopes in operation or in development.

THE PHYSICAL AND CHEMICAL EVOLUTION OF THE EARLY SOLAR SYSTEM AND PREBIOTIC EARTH

The stage for the emergence of life was set long before the rise of prebiotic chemistry. Condensation of the solar nebula, disc formation, stellar activity, planetary accretion and differentiation, and the composition and impact frequency of asteroids and comets all determine the conditions within which life might emerge and survive. All of these factors, and more, are pivotal to ensuring the presence of the necessary environmental and geological conditions and elements that give rise to prebiotic molecules and then biotic chemistry on a planet or a planetary body. Looking forward, emergence-of-life research will remain focused in the solar system and will require a broadening of perspective that integrates answers to the following questions:

1. *Habitability of the early Earth*—What processes and parameters were critical to Earth's habitability as the Sun and the young solar system co-evolved? How can this knowledge inform investigations for the habitability of other bodies, including exoplanets?
2. *Carbon and volatile inventory of the prebiotic Earth*—What characteristics of the carbon and volatile inventories of prebiotic Earth, and of the solar system architecture that delivered them, are relevant to the emergence of life?
3. *Conditions on the prebiotic Earth*—Can the many, co-varying parameters giving rise to emergence-of-life conditions in prebiotic Earth environments be better constrained?

Habitability of the Early Earth

What processes and parameters were critical to Earth's habitability as the Sun and the young solar system co-evolved? How can this knowledge inform investigations for the habitability of other bodies, including exoplanets? Many phenomena related to the early evolution of the solar system were critical to the habitability of the terrestrial planets in general, such as Venus and Mars, as well as Earth and probably a number of the satellites around the gas giants, including Europa, Callisto, Enceladus, Titan, and possibly others. Thus, understanding the creation of a habitable environment for the Earth in terms of the emergence of life is relevant for the other bodies in the solar system and beyond as well. These include physical as well as chemical parameters. Starting at the beginning of planetary accretion from clumping of the dust/particle/gas nebula, distance from the Sun conditioned the formation of rocky planets closer to the Sun, within just over 1.5 AU, and gas/ice planets further out, and beyond Jupiter at 5.2 AU, with the Main Asteroid Belt objects orbiting between Mars and Jupiter. Although intensely studied, the physical and mechanical processes leading to the initial creation of rocky objects are not clearly defined. For example, it is unknown if accretion was localized or involved the whole of the protosolar disc; how the temperature gradient within the disc affected chemical differentiation; and to what extent the formation and timing of formation of Jupiter and Saturn affected the composition of the reservoirs of material for accretion in the inner and outer solar system (e.g., Kruijer et al. 2017). Modelling of planetary formation by the group of Morbidelli et al. (2016), for example, suggests that the formation of Jupiter effectively created a “fossilized snow line” sun-ward of which the accreted bodies were effectively volatile poor. This raises the question of how and when volatiles were transported into the inner solar system.

Carbon and Volatile Inventory of the Prebiotic Earth

What characteristics of the carbon and volatile inventories of prebiotic Earth, and of the solar system architecture that delivered them, are relevant to the emergence of life? Small bodies, such as asteroids, planetesimals, and comets, are likely to have delivered to the Earth organics and volatiles necessary for the emergence of life. Models suggest that the volatile-rich carbonaceous chondrites could have been scattered into the inner regions very early during the accretion process, with water accreted on the early Earth within ~100 My (Raymond and Izidoro 2017). What is the relationship between comets and the primitive asteroids in the outer solar system that gave rise to carbonaceous chondrites? Do they represent end members of a continuum?

Debate continues about the timing and effects of instabilities in the orbits of the giant planets, which affected cometary bombardment and importation of volatiles including water and organics to the inner planets. Evidence of this cometary bombardment comes from Xe isotope study of 67P/Churyumov-Gerasimenko by the Rosetta suite of instruments, which shows that about 22% of atmospheric Xe comes from comets but that this accretion was a late veneer, after planetary differentiation (Marty et al. 2017). What was the contribution from later cometary and carbonaceous chondritic components in terms of timing, composition and quantity? Present estimates suggest that only ~2% of the late veneer is cometary in origin.

Are there relics of prebiotic chemistry remaining on Earth, Mars or elsewhere that might be informative? Where might these be and how might we detect them, analyze and correctly interpret them? Studies of volatiles on satellite moons, such as Titan, and on comets and asteroids provide valuable details for understanding the heritage, formation and possible delivery of organics to settings conducive to the emergence of life. Studies incorporating data from the atmosphere of Titan show that, even in a more neutral atmosphere, organics and possibly even an organic haze could have formed in the atmosphere of the early Earth (Trainer 2013). These investigations can be extended to include continued study of organics in available extraterrestrial material on Earth (micrometeorites, carbonaceous chondrites, and returned samples), as well as investigation of the organic inventory on a planet, such as Mars. Although the oxidising and irradiated conditions existing at the surface of Mars destroy especially the more volatile component of the organics, the exogenous component could be preserved at depths below 1.5-2 m (Kminek and Bada 2006) targeted by the the European-Russian ExoMars 2020 rover (Vago et al. 2017).

Conditions on the Prebiotic Earth

Can the many, co-varying parameters giving rise to emergence-of-life conditions in prebiotic Earth environments be better constrained? There is increasing focus on the role that specific early Earth environmental conditions played in the development of prebiotic chemistry. The fundamental chemistry of life is based on oxidation/reduction reactions;that is, the chemistry of electron transfer. The oxidation/reduction reactions that drive prebiotic chemistry rely either on chemical and thermal disequilibria generated at Earth cools or by solar ultraviolet radiation. In either case, a primary product is often hydrogen. This process can be supported by the thermochemical alteration of olivine to serpentine (serpentinization), by radiolysis of water, or by populating the antibonding orbitals of transition metals in aqueous phase by photons. The hydrogen can be used to form reduced carbon, and potentially to reduce dinitrogen gas to ammonium. Reactions with transition metal containing minerals (e.g., iron sulfur clusters) can potentially lead to prebiotic catalytic reactions.

Attempts are being made to arrive at a more realistic understanding of the variety of local environmental conditions that could have affected the formation of critical prebioic molecules and, eventually, the emergence of life. Westall et al. (2018) reviewed current understanding of the geological/geochemical environment of the early Earth, together with various environmental scenarios that have been proposed for the emergence of life. Each of these scenarios presents certain advantages and disadvantages, but at the present time there are insufficient data to conclude that any one scenario stands apart as being most conducive to life's origins. There is a lack of scientific understanding regarding how life originates on a suitable planet, other than the recognition that it involves the interplay of environmental fluxes, both energy and raw materials, to drive plausible chemical pathways.

Nonetheless, substantial advances have been made in recent years with regard to potential scenarios for the origin of life on Earth, fostered by consideration of plausible early Earth conditions (Dass et al. 2016). For example, the potential importance of hydrothermal systems for the emergence of life has long been understood (e.g., Baross and Hoffman 1985), but recent experiments that sought to recreate these environments in the laboratory have shown how hydrothermal systems can support the synthesis of prebiotically-relevant compounds such as methane and amino acids (Suzuki et al. 2015; Kobayashi et al. 2017). Other experiments that adopt a systems chemistry approach have shown how selective crystallization and other geochemical fractionation processes can sequester key intermediates for the prebiotic synthesis of biomolecules (Patel et al. 2015).

In future, the experimental approach to prebiotic chemistry will be have an increased focus on integrating the multi-parameter space of early Earth environments and their covariance (Dass et al. 2016; Westall et al. 2018). This opens the possibility of exploring the environmental mechanisms that foster accumulation, differentiation, and preferential selection of what was likely to be a highly diverse mix of prebiotic precursors. Furthermore, multi-parametr focus will help elucidate the environmental and chemical sequences that led to the emergence and selection of more complex and refined prebiotic molecules. On longer timescales, better understanding of the intimate ties between planetary processes and life's evolution can be applied to better understand the coevolution of the planet and its biosphere, the expansion of life's limits through adaptation to changing planetary environments, and the evolution of biological complexity. An understanding of these coevolutionary processes can then be applied to the search for life outside the solar system taking into account increased knowledge of dynamic and evolving habitability and the conditions and mechanisms that might lead to atmospheric biosignatures, such as an inventory of thermodynamically unlikely gas mixtures such as seen on the Earth today.

Pathways to Understanding the Evolution of the Early Solar System and Prebiotic Earth

Understanding the prebiotic inventory of exogenous materials, and how they were and are distributed through the solar system, is and will continue to be challenging. To make progress in this line of research requires study of the original material in situ on the small body or in returned samples. Sample analysis will need to be paired with investigations of the effects of the space environment, such as radiation, changes in temperature, and effects of a vacuum, on analog and recovered materials. For returned sample, studies pertaining to sample alteration due to atmospheric entry will also be important. In the past, questions surrounding small body composition and contribution to the organic and volatile inventory of the solar system have been addressed by in situ and sample return missions to comets (e.g., Stardust and Rosetta) and asteroids (e.g., Hayabusa). Looking into the next twenty years, this will continue to be a robust area of research with great potential for discovery.

In the near term, the Japan Aerospace Exploration Agency (JAXA) Hayabusa 2 mission will return samples that may be organic rich or contain hydrated materials from the asteroid Ryugu. Shortly thereafter, in 2023, NASA's Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS-REx), will return to Earth samples from the asteroid Bennu that are hopefully rich in informative volatiles (Lauretta 2017). In the longer term, a comet nucleus sample-return mission was recently selected by NASA for further study. Its proposed goal is to return to comet 67P/Churyumov-Gerasimenko, which was originally visited by Rosetta. One of the mission goals is to capture a sample of organics and volatiles and return it to Earth for analysis (Squyres 2018).

Both for the emergence of life on Earth, and especially when considering the possibility of life beyond the Earth, it is essential to consider a range of geophysical and geochemical scenarios. Laboratory studies of the various scenarios will continue to be important, especially when backed by an understanding of the geological record and modeling efforts that help to constrain parameters such as temperature, pressure, ultraviolet flux, and the concentration of key starting materials. It also is useful to consider what areas of parameter space are out of bounds, either because they are implausible for the planet being studied or because they defy the principles of chemical reactivity. Progress in this area will depend on the collaborative interaction among scientists from multiple disciplines and an integrative view of how to explore putative early Earth scenarios via experiments, field work and modelling with an open mind regarding possible pathways to life. Early Earth investigations in fact provide important "test bed" opportunities in which community developed initiatives such as a Comprehensive Framework for Life Detection can be most tractably tested and refined, Such "missions" to Early Earth can catalyze vital conceptual progress and feed forward into mission planning and implementation in the search for life elsewhere in the universe.

DYNAMIC HABITABILITY: COEVOLUTION OF LIFE AND ENVIRONMENT

Planetary habitability depends as much on planetary evolution and solar system dynamics as it does on genomic mutations and ecological successions. Planetary conditions enabled life. When life emerged, planets and putative planetary biospheres evolve together through time such that the initial conditions from which life arose are not necessarily the same as those that subsequently gave rise to local-scale or planet-wide habitability. This coevolution can be direct and causative, indirect, fundamentally disconnected, or stochastic. While the Earth is presently our singular example of planetary and biosphere coevolution, nearby terrestrial planets have their own geologic history. Together, the geologic records of the rocky planets in this solar system can be applied to better understand how their planetary dynamics and potential biospheres did or did not co-evolve. These principles apply to habitable exoplanets as well, although we are far from having data to apply them. Comparative planetology can extend these lessons beyond the inner solar system. Informed by recent trends in assessing planetary habitability, the following questions are likely to guide this field of research in the next 20 years.

1. *Predictable elements of planetary evolution*—What elements of planetary evolution are predictable and independent of biosphere evolution?
2. *Feedback between biosphere and geosphere*—What feedbacks exist between the biosphere and geosphere, including during long periods of quiescence?
3. *Periods of catastrophic change*—How do periods of catastrophic change reflect the balance of influence between planetary dynamics and the biosphere?

Below, we provide a description of the key research goals and enabling missions and technologies needed to answer these questions.

Predictable Elements of Planetary Evolution

What elements of planetary evolution are predictable and independent of biosphere evolution? Evaluating those aspects of Earth's evolution driven exclusively by planetary dynamics is difficult because of accompanying changes in the global biosphere, its impacts on surface and subsurface environments, and incomplete understanding of feedbacks between a biosphere and planetary processes. As such, Earth represents one planetary trajectory—one with a sustained and active biosphere. Mars and Venus serve as examples of other planetary trajectories—ones expressing interactions between planetary surface processes, interiors, and atmospheres potentially without extant life or a known, sustained biosphere. These trajectories are pivotal to identifying which aspects of the planetary conditions are predictable and occur independently of biosphere evolution. By extension, they can be used to identify which planetary dynamics are affected by a global biosphere, and how such feedbacks are recorded. Taken together, understanding these interactions will enable the development of models that span the possibilities of planetary trajectories. New research suggests Venus may have been habitable early (e.g., Way et al. 2016) with oceans that may have extended into the past billion years, suggesting a rapid shift in conditions. Therefore, Mars and Venus are ideal candidates to develop models of the evolution of rocky planets under different forcing. Together, Earth, Mars and Venus can be used to develop trajectories in planetary evolution and punctuated or sustained habitability and to understand how the endogenic and exogenic factors that change the planet locally, regionally, and globally combine to drive shifts in the environment.

Feedback between Biosphere and Geosphere

What feedbacks exist between the biosphere and geosphere, including during long periods of quiescence? Earth's own history provides the only current opportunity to identify the feedbacks between planetary dynamics and biosphere evolution over global and geologic time scales. The Hadean Earth was starkly different compared with today's familiar surface. Since then, evolution in the biosphere has clearly driven major changes to the geosphere, most notably the Great Oxidation Event (GOE) at ~2.45 Ga. However, long periods of time appear to be relatively quiescent—for example, the so-called (but actually not-so) Boring Billion years (1.8 to 0.8 Ga ago) during which it has been suggested the oceans may have been largely sulfidic (Poulton et al. 2004). Although pivotal changes were occurring during these periods (e.g., Mukherjee et al. 2018) that set the stage for periods of subsequent rapid, catastrophic change, the feedbacks between discrete evolutionary events in the geosphere and biosphere are poorly understood. Whether this is inherent to the feedbacks themselves, for instance if they became decoupled, buffered, or stochastic, if it is an artifact of the incomplete record, preservation bias, or if the feedbacks during these periods simply occurred below the detection threshold of modern methods, is not known.

Moving forward, understanding these long stretches of stability will become as important as understanding the catastrophic events. When considering other planetary surfaces, Earth's own record shows that quiescence or stability is, geologically, the more prevalent state. As such, quiescent states are also likely important on other planets and could be well preserved and revealed through exploration. Further, periods of quiescence hold the key to understanding the influence of stable organisms on the planet's geosphere. For example, many organisms would have had to find refuge in the oxygenated photic zone if the Proterozoic oceans were indeed sulfidic. Studying such periods will not only inform whether or not a continuous biosphere maintains a planet's habitability, but also will help identify potential biosignatures by which such organisms might be recognized.

Periods of Catastrophic Change

How do periods of catastrophic change reflect the balance of influence between planetary dynamics and the biosphere? Although periods of quiescence may hold the key to systematically understanding the feedbacks between biosphere and planetary dynamics, geochemical and geological evidence simultaneously suggest that life's innovations and catastrophic environmental change may be coupled. This has been shown for punctuated events and extended phases of planetary evolution that involved rapid change as has been suggested, for example, during Snowball Earths. Snowball (or slushball) Earths it is argued were precipitated by continental configuration and changes to planetary insolation, which together accelerated ice accumulation over the continents and plunged the Earth into icehouse conditions. Despite this drastic change in global environmental conditions driven by planetary dynamics, life persisted. Not only did life persist, it is thought to have been pivotal in the recovery of the Earth's climate. A rapid, second rise in atmospheric oxygen followed the Neoproterozoic icehouse periods and appears to be associated with the radiation and expansion of eukaryotic algae (Brocks et al. 2017). The close association of these events suggests that changes in the biosphere (most likely precipitated by icehouse conditions) in turn altered Earth's environment. To what extent is presently unclear. It has also been suggested such events may have played a role in triggering the Cambrian radiation for instance (Canfield et al. 2007). These examples demonstrate that the interplay of planetary conditions and the biosphere can be critical to planetary and life's evolution. The relative influence of planetary dynamics versus the biosphere also changes with time. In contrast to periods of quiescence, which may represent a balanced influence of planetary evolution and life's influences, periods of catastrophic change may represent an imbalance in influence. Further research on both of these modes will significantly advance understanding of the coevolution of life and its environment on both this planet and on other planetary bodies including exoplanets.

Pathways to Exploring Dynamic Habitability and Comparative Planetary Trajectories

Incomplete records, preservation biases, and detection limits as discussed in Chapter 4 all pose challenges to exploration of Earth's deep past and the feedbacks between life and environment expressed in its record. Field-based research, experimentation, as well as models, provide an important path forward. Systems models are growing increasingly sophisticated. Models that capture interactions between the ocean, atmosphere, and weathering cycles or metabolic and ecological parameterizations have the potential to evolve into models capable of tracking both geological and biological conditions that might enhance or detract from habitability.

Understanding the coevolution of life and the Earth's environment over time is important for understanding planetary trajectories and, by extension, predictive models of potentially habitable planets in the solar system, such as ocean worlds. During its early stages, Earth itself was an alien planet by current standards, and might not have been recognized as habitable despite being widely inhabited. Thus, Earth provides a foil to planets in the solar system currently thought to be uninhabited, notably Venus and Mars. In turn, these planets can be used to aide in the identification of global-scale feedbacks between life and its environment here on Earth by providing abiotic baselines. This will require modeling the trajectories of Mars and Venus, both of which followed similar early planetary conditions but resulted in drastically different outcomes. On Mars, the InSight mission, as well as the ExoMars rover to be launched in 2020, have instrumentation for making gravity, radar, and seismic measurements. Both will help to reveal the planet's internal structure, feeding into models of planetary evolution and dynamics. Without a series of planet-wide geophysical platforms however, full understanding of the martian interior structure could remain elusive. On Venus, a path forward is less clear. The Russian Venera-D mission, proposed to launch in 2026, may be a precursor to a landed mission, although this remains undecided. Many Venus missions, focusing on science from the atmosphere to the surface, have been proposed through the New Frontiers and Discovery programs, but have as yet to be selected.

In the next 20 years, this line of research may provide the ability to predict how a different early evolution of life may have led to a modern Earth surface drastically different from today's, or, conversely, how a different early trajectory in Earth's dynamics could have changed the evolution of life today. Such a model would draw together understanding of fundamental, planetary geodynamics learned from comparing rocky planets that may or may not be inhabited, juxtaposed with understanding the feedbacks between the biosphere and planetary dynamics as evidenced in the rock and paleogenomic records on Earth. Those fundamental advancements would then be able to inform understanding of other models of life—even potentially weird life—and biosignature science essential to the search for life on ocean worlds and exoplanets.

DIVERSE HABITABLE CONDITIONS AND SUBSURFACE WORLDS

The Earth may represent only one end-member of a life-hosting planet, even among bodies with similar initial conditions and geophysical processes. The deep subsurface on Earth, Mars, terrestrial planets in other systems, and the ocean worlds, all have a diversity of environmental conditions that share some degree of similarity, and could be habitable in similar ways. Examples include subterranean water reservoirs on Mars and other planets, and modern day oceans in contact with rock on the outer moons. Can subsurface life exist in the absence of surface life? That is, can we distinguish whether the surface biosphere is an outgrowth of the subsurface biosphere, or is the colonization of the subsurface facilitated by surface phototrophy? Growing sophistication in our understanding of life and its trajectory on this planet could reveal much about how life could persist on exotic worlds. The exploration of these worlds gives us the chance to search for a second genesis of life and even to study an alternative biochemistry if enabled by advances in astrobiology. The committee has identified four key lines of research that need to be addressed over the next 20 years:

- *Adaptation to extreme environments*—How does life adapt when subject to it its environmental and energetic limits?
- *Chemosynthetic and rock-hosted biospheres*—How can marine and continental subsurface terrestrial analogs help define what a chemosynthetic or rock-hosted biosphere might look like on another rocky planet, or on an ocean world?
- *Habitable environments in the martian subsurface*—What is the spatial and temporal distribution of subsurface water, the sources and sinks for methane and other reduced gases such as hydrogen, and the relevant water-rock reactions capable of sustaining habitable environments in the subsurface on Mars?
- *Habitability of ocean worlds*—What are the chemical inventories and sources of energy that could generate habitability on ocean worlds, and what processes sustain these inventories?

Adaptation to Extreme Environments

How does life adapt when subject to it its environmental and energetic limits? Our understanding of the limits of life is continuously updated as we document and discover microbial communities thriving in nominally "extreme" environments, where perceived extremes of temperature, pressure, pH, salinity, energy, etc. are actually preferred conditions for the organisms that thrive in these conditions. From slow life living in energy-starved environments, to those that thrive in extremes of temperature, radiation, and pressure, life on this planet has become well adapted to its conditions. Understanding the genetic tracers of adaptation could, simultaneously with the rock record, inform how life has adapted, and help retrace the history of life on Earth. For low temperature organisms, for instance, at the coldest temperatures recorded for survivability and activity, many organisms also have extraordinary radiation tolerance. Does this tolerance derive from the ability to repair cellular and DNA damage, or is it a relict of prior environmental stress (e.g., survival in desiccating environments)? While significant progress has been made in understanding the adaptations of organisms to one parameter (e.g., temperature, low water activity), there is an urgent requirement to understand life's response and ability to adapt to multiple parameters (combined effects of extreme temperature and pressure for instance).

How long can dormant or slow-growing cells can remain viable? Reports that cells from 250 My salt deposits had been resuscitated (Vreeland et al. 2000), are now largely attributed to later contamination (Graur and Pupko 2001). Studies of 600 Ky old permafrost showed that the DNA in the cells contained in it could still be replicated, but not in older permafrost (Johnson et al. 2007). These studies suggest that low-level gene repair in a very slowly metabolising cell is better for cell viability than dormancy, but these are some of many issues that remain unresolved and controversial.

How does life adapt to environments in which habitable conditions are heterogeneous in space and time? Some of the most notable examples of slow-growing microbial systems are those hosted in the Earth's continental or ocean crust, or in deep-sea sediments. Marine sediments have been shown to host viable cells down to depths of nearly 2 km, but metabolic turnover rates may be as slow as one cell division every thousand years (Kallmeyer et al. 2012; Ciobanu et al. 2014). How do organisms adapt to such slow time scales and what are the approaches to interrogate life occurring on a scale so fundamentally different from the scale of human investigations (Trembath-Reichert et al. 2017). In fractured continental crust, water infiltrating deep fractures has entrained microbes over long periods of time to depths of between 3 and 4 kilometers (Onstott 2016). Due to water–rock reactions such as serpentinization and radiolysis, individual fractures, sometimes as small as 1 cm, may be a relative oasis in what is an overall oligotrophic environment. The discovery of preservation of habitable fluids on billion year timescales in the Earth's deep continental crust (Holland et al. 2013; Warr et al. 2018) have defined new frontiers in research on habitability and microbiology that can help address the question of long-term survivability of both extant ecosystems and preservation (or lack thereof) of biosignatures of past subsurface life.

Chemosynthetic and Rock-Hosted Biospheres

How can marine and continental subsurface terrestrial analogs help define what a chemosynthetic or rock-hosted biosphere might look like on another rocky planet, or on an ocean world? Given the prevalence of life on Earth that exists without direct influence of the Sun, alongside the harsh surface conditions encountered on the most compelling bodies in the solar system, subsurface environments in general may prove to be more habitable than planetary surfaces. The realization that habitable zones in the subsurface can host complex ecosystems that exist independently of surface energy sources has encouraged the search for fossil biosignatures in a wide range of subsurface geological settings on Earth. These places host a subsurface paleontology that includes a variety of biomediated microfabrics and textures (see Hofmann and Farmer 2008; 2000). In association with distinctive suites of morphological biosignatures, biogeochemical indicators of past life, (see Chapter 4 " and references therein), and concentrations of bio-essential transition metals (that are required to sustain enzyme functions) may be investigated. Exploring such suites of bioindicators is arguably the most productive approach for subsurface exploration, and is most useful when conducted in tandem with strategies to determine how to efficiently translate this information to other planets and moons (for example via spectral indicators of concentrated materials, or targeted fly-by or in situ missions).

Importantly, given the different evolutionary pathways that such planets may have experienced, different types of ecosystems might be expected. Over the next twenty years, growing sophistication in understanding exotic conditions on Earth could provide key information for elucidating how a chemosynthetic or rock-hosted biosphere might operate on another rocky planet or ocean world. Exploration of the deep sea floor by drilling projects and in situ vehicles, and parallel investigation of the rock record through deep time will expand our picture of the evolution of subsurface habitability. Although early anaerobic Earth is likely the largest terrestrial analog environment in which rock-hosted chemotrophic life once flourished, analog studies of modern terrestrial systems still provide the most readily actionable activities to address questions about the processes governing subsurface habitability and the nature, diversity, and preservation of both extant and extinct subsurface communities. Given the recent focus on the habitability of ocean worlds, research will need to continue on energy-rich environments, such as hydrothermal vents and marine sediments. An increasing focus on terrestrial subsurface communities, including oligotrophic, rock-hosted, continental subsurface communities, however, has even greater potential for novel discoveries at present because in many cases so much less is known. Similarly subducted minerals possibly containing direct and indirect evidence of biological processes can be targetted (Hazen et al. 2008). Lessons learned from these environments facilitate process-based thinking about life that can be directly relevant to mission planning. Astrobiology is not just about the search for extraterrestrial life, but also the broader scientific understanding of how habitable planets form, what makes them habitable, and the processes that sustain life.

Habitable Environments in the Martian Subsurface

What is the spatial and temporal distribution of subsurface water, the sources and sinks for methane and other reduced gases such as hydrogen, and the relevant water-rock reactions capable of sustaining habitable environments in the subsurface on Mars? Continued advances in understanding extreme life on Earth coupled with discoveries from the martian surface and near subsurface environments have driven a revolution in thinking about Mars' habitability. Not only the spatial and temporal distribution of surface and subsurface hydrology, but also the characteristics of that water through time have challenged preconceptions about surface and subsurface habitats, including the potential for ephemeral niches and isolated refugia, and related topics such as the production of reduced gases such as methane (Ehlmann and Edwards 2014; Ehlmann et al. 2015, Grotzinger et al. 2015; Goudge et al. 2016; Ehlmann et al. 2016; Webster et al. 2018). The high radiation flux on the surface of Mars may be the driver for life to seek refuge underground. Discoveries of the persistence of life in the Earth's subsurface, of the ability of life to adapt to extremely slow growth rates under anaerobic and oligotrophic conditions (Ciobanu et al. 2014; Trembath-Reichert et al. 2017), and of preservation of habitable fluids on billion-year timescales, have further defined new frontiers in research on martian habitability and microbiology. These new frontiers, and the diversity of discoveries that support them (see Chapter 4) have yet to be fully leveraged by the Mars exploration program. However, technological advances and the future missions they enable will begin to address these new frontiers. Several instruments on Mars 2020 are designed to address the past habitability of Mars. In particular, the Scanning Habitable Environments with Ramen and Luminescence for Organics and Chemicals (SHERLOCK) and x ray fluorescence spectrometer (PIXL). Samples cached by Mars 2020 will be returned to Earth for analysis on a future, but currently unscheduled, mission.

Despite the advances that continue to be made in understanding terrestrial subsurface communities, accessing the subsurface systems on other planets to advance the goals of astrobiology remains challenging. Technological advances to address this challenge, however, are on the horizon. ESA's ExoMars 2020 lander will take the first steps toward that goal with its objectives to search for past and extant life. That search will include the geological and environmental context of the surface, and sampling down to a depth of 2 m (Vago et al. 2017; Vargo 2018). While the radiation damage from solar ultraviolet and energetic particles on Mars is literally "skin deep", the secondary effects from galactic cosmic rays can destroy organics down to ~1.5 to 2 m (Kminek and Bada 2006); Pavlov et al. 2012). This will be the first instance of drilling to any substantial depth into the surface materials of another planet. Furthermore, it will have scientific value of collecting samples below, or at the lowest depth, of the penetration of ionizing radiation while also reaching below the depth of surface oxidation. It is hoped that samples from below 2m will contain preserved organics that may, potentially, provide signatures of life. This material will be analysed by the Mars Organics Molecule Analyser, which includes a laser desorption and a gas chromatograph-mass spectrometry mode (Goesmann et al. 2017).

While considerable community activity is focused on developing drilling technologies (Antilla 2005; Stamenkovic et al. 2018), it is important to recognize that there are a wide variety of strategies for accessing subsurface samples and investigation of subsurface processes. Indeed drilling is not the only approach for studying the subsurface. Geophysical instrumentation provides a broad array of non-invasive strategies to advance understanding of subsurface processes. For example, the recently launched Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission will provide data relevant to the martian subsurface. InSight's heat probe will penetrate the subsurface to several meters and together with its seismometer will provide information on planetary seismic activity ("marsquakes"), and on heat (and possibly volatile) transport directly relevant to astrobiology (Banerdt et al. 2013). Similarly, the ExoMars 2020 rover will carry the Water Ice and Subsurface Deposit Observation on Mars (WISDOM) ground-penetrating radar (GPR). The radar will sound the subsurface with a vertical resolution on the order of centimeters down to a depth of approximately 3 m. In addition to being of scientific value in and of themselves (for reconstructing surface deposit structure and constraining subsurface materials, potentially including fluids, volatiles, or clathrates), radar observations can be fed forward to identify drilling targets and hazards as well as optimize drilling operations.

Additional non-invasive techniques for studying the subsurface, and for gathering samples, exist. Geomorphological features such as seeps, scarps, impact craters, as well as fractured terrains, lava tubes, and ice caves all provide alternative means of accessing samples that originated in the subsurface (e.g., white paper submissions Blank et al. 2018, Davila et al. 2018, Vance et al. 2018). If obtained, such samples, although altered by contact with the surface, are still likely to contain information on subsurface processes. High resolution orbital images have already provided numerous examples of locations (e.g., Boston 2010; Oehler and Etiope 2017) that could be followed up with ground-penetrating radar and seismic sounding observations. Small satellites delivered as secondary payloads are capable of monitoring large areas of the planet at lower costs and can complement rover exploration missions by accessing sites that rovers cannot reach.

Looking to the future, an integration of the multiple approaches described above could address the role of subsurface processes in governing habitability, the preservation of habitable environments, and the preservation of biosignatures. This is a growing need identified in recent studies (e.g., MEPAG 2015; MEPAG HSO-SAG 2015). Subsurface geophysical, geochemical, geological, hydrological, and potentially biological processes are vital to understanding habitability from local to global scales. The remarkable discoveries of methane and its variability on Mars (Webster et al. 2018; 2015) underscore the relevance and urgency of such subsurface-focused activities for astrobiological investigations of both the rocky planets, and the new frontiers provided by recent discoveries on ocean worlds and exoplanets.

Habitability of Ocean Worlds

What are the chemical inventories and sources of energy that could generate habitability on ocean worlds, and what processes sustain these inventories? The ocean worlds of the outer solar system are compelling both due to their potential for extant life as well as for exotic life as we do not know it. For ocean worlds such as Europa and Enceladus, where saline oceans exchange material and energy with an ice shell and potentially active seafloors, the question remains to what extent water-rock reactions may have progressed, whether they are still ongoing, whether planetary interiors were ever or are still active, and how interactions between their oceans and surfaces mediated by their ice shells might support active biospheres. Estimates for the salinity and pH range of these oceans span a range of environments on Earth, from neutral and low-salinity to much more extreme conditions, which need to be better constrained, along knowledge of the origins and limits of life, in order to understand their potential habitability, and finally whether they are inhabited. Discovery of life here that originated separately but in potentially similar conditions to that on Earth would transform our knowledge, and requires access to the ice and liquid water processed through and below it. For Titan, measuring the details of potentially complex prebiotic organic chemistry, and understanding the extent to which surface reservoirs interact with the ice and ocean below provide keys to understanding the kinematics and organization of an exotic chemical playground in which a separate origin could be possible. In any of these worlds, the distribution of CHNOPS, the lifetime and pathways of critical compounds from the surface to the subsurface, and the degree of interaction between various reservoirs within these worlds is unknown. Spacecraft mission and concept development are being guided by and will continue to benefit from the exploration of Earth's subsurface systems because terrestrial water-rock interactions have implications for the production of reduced gases on Enceladus and Europa. Recent discoveries of metabolisms fuelled by natural radiogenic energy, such as the radiolysis of water at the rock/water interface used by sulphate reducing bacteria deep in the Earth's crust (Lin et al. 2006; Li et al. 2016) are relevant to the development of strategies for searching for life on icy, ocean worlds.

Missions to the oceans of Europa, the lakes of Titan or the plumes of Enceladus, with instruments capable of analyzing long-chained organics, could revolutionize our understanding of ocean worlds. Lake floaters, small fissure explorers, and other surface and subsurface explorers could deliver advanced instrumentation to search for biosignatures on these planets. The ocean worlds cannot be explored in the same way as the terrestrial surface or the surface of Mars, because the conditions are different, and the planets have been subject to different dominant processes. The development of instruments to explore them needs to be be informed by research discoveries in the context of subsurface habitability, as key science questions for ocean worlds will require subsurface access, through the ice or into lakes where putative biospheres could thrive.

Vigorous program support and intense focus on the icy moons could, in the next 20 years, go as far as planning a subsurface expedition to an Ocean World. Exploration under the ice on Europa or another Ocean World has attracted the interest of not only NASA but also ESA. Both agencieshave funded large-scale analog science and engineering activities to make these missions possible in the not so distant future. Achievements in underwater and under and through ice missions and scientific analysis on Earth can drive the development of science questions, innovative instrumentation for in situ analyses, and both engineering and operations scenarios needed to make long-term subsurface missions possible. If driven by astrobiology and science community participation, in a new interdisciplinary and interagency landscape that prizes innovation and achievement, such missions are possible within the next few decades. Europa Clipper and Jupiter Icy Moons Explorer (JUICE) will be launched in the near future. A Europa lander is also under consideration for launch to Europa in the 2020s. In order to search for life on the icy satellites, it will be necessary to sample the plumes and material deposited on the icy crust in the immediate vicinity of the plume exit points. The biologically interesting material will be rapidly degraded by radiation. The nature of the missions to these icy satellites orbing the high radiation belts of their host stars makes these missions highly challenging from the technological point of view. The success of the Cassini-Huygens mission to Titan, albeit with a significantly lower radiation load, shows that these challenging missions can be accomplished. In the longer term however both in situ measurements and sample return will be needed for a complete understanding of these interesting planetary bodies. Technological advances in terms of protected and cooled sample return capsules need to be developed.

In the outer solar system, conventional photosynthetic processes may be highly limited, if possible at all. Thus, any biosphere is more likely to derive its energy from alternate ranges of the electromagnetic spectrum (e.g., by using infrared rather than visible radiation) or be similar to chemosynthetic or rock-hosted communities on Earth. Therefore, the ocean worlds of the outer solar system are the likeliest to answer questions about what alternative biospheres might look like on another planet and what processes of energy cycling they use. Europa Clipper, currently slated to launch in early-to-mid-2022, is the first systems-level mission to an ocean world, and the first motivated primarily by characterizing the moon's potential for habitability. This Jupiter-orbiting, multi-flyby spacecraftwill carry instruments for sampling plume or sputtered surface materials to assess chemical composition and the nature of Europa's non-ice materials. The spacecraft will also carry the capability for magnetic sounding of the ocean and core, near-infrared spectroscopy of surface materials, imaging, and radar sounding of the ice shell. Not only will this suite of instruments study the surface of the moon and begin to assess the structure of the ocean's icy shell, including perched water bodies and putative water-filled fractures and shallow brine zones, it will also be able to characterize the nature of the sea floor and the moon's rocky core via gravity, allowing better models of the global energy budget. ESA's JUICE mission to Ganymede will conduct similar investigations to potentially reveal the nature of its interior, perhaps revealing how ocean worlds with deep high-pressure icy mantles could yet maintain habitability.

Candidate lander missions to the ocean worlds currently under study for possible flight in the 2020s include a Europa lander concept (Hand et al. 2016) and a Titan rotorcraft (Lorenz et al. 2017). The Europa lander as currently envisaged would sample in the shallow subsurface to extract ice samples, characterizing them for composition and potential biomarkers, as well as characterizing the ice shell structure using seismometers. A lander with the ability to get below the likely sterilized upper surface layers would increase the fidelity of information about the habitability of Europa. The rotorcraft concept would explore Titan's surface and lakes by flying across and making multiple landings to explore Titan's atmosphere, diverse surfaces, and organic chemistry. Prior versions of these types of missions also exist, including more expansive instrumentation and deeper drilling by the 2012 Europa lander concept and the proposed Discovery mission that was intended to land in and float across one of the moon's large seas.

While landing missions on ocean moon surfaces remains a mid-term goal, nearer-term opportunities using technology that is already well developed exist to constrain the chemical inventories on ocean worlds, to evaluate the processes that sustain these inventories, and to search for signs of life. Alternative methods have been envisaged such as measuring chemical complexity or capturing samples from plumes of material ejected from these worlds. For example, in the discussion of life detection at Enceladus, there is debate as to whether remote plume characterization by biosignatures that consider molecular composition, organic complexity, and Gibbs free energy is sufficient. The alternative is direct sampling by obtaining a plume sample during a fly-by and analyzing that sample onboard or returning it to Earth. Plume characterization via remote-sensing or by in situ analysis of material captured during fly-by requires appropriate instrumentation packaged in a manner consistent with typical power, mass, volume, data rates, and cost limitations inherent in any mission to the Saturn system. In situ characterization or sample-return optionsrequire the collection of sufficient material, in its original state, to undertake the requisite analyses.On Earth, the common practice for DNA extraction or microbial characterization in the oceans—which are known to teem with life—is to filter multiple liters of water to gain enough material to get good signals. At Enceladus eruption rates, and assuming 10^7 cells/cc, in order to expect to collect a cell from a plume an estimated 12,000 km of plume flybys would be needed, before even considering what has happened to the sample by the time it reaches a spacecraft (Hand 2015; Lorenz 2016). Return options will necessitate long flight times—i.e., to Saturn and back to Earth in the case of an Enceladus plume sample-return mission—and samples collected may be compromised if they are collected when flying through the plume at too great a velocity. For Titan, the development of an agnostic approach to searching for life will be critical in order to interpret any samples from its hydrocarbon lakes, underscoring the progress on biosignatures required and discussed in detail in Chapter 4.

The foregoing missions will provide a new wealth of data to deepen our understanding of how habitable systems arise, and provide links to lessons from the Earth. Comparisons between the ocean worlds and the Earth will further the discussion of systems-level interactions across a wide range of scales and a broad set of conditions pivotal to astrobiology. Increased understanding of ocean world habitability is almost certain, and perhaps progress can be made in measuring statistical and direct biosignatures from an ocean world through particle and compositional analyses.

Revolutions in small satellites could also provide opportunities to explore the nearby environment or surfaces of the ocean worlds. Cubesats could accompany larger missions to measure chemistry in plumes or act as small surface payloads. Small instruments are already under development that could fly on these missions such as imagers, dust detectors, and miniature mass spectrometers (see Chapter 5"). At the same time, JWST and the proposed next-generation space-based observatories—e.g., LUVOIR, HabEx, and OST— planned to support exoplanet and cosmic origins sciences, together with existing ground-based telescopes—e.g., the Atacama Large Millimeter Array (ALMA)—and the various GSMT projects under development could provide observations relevant to studies of the ocean worlds in between dedicated spacecraft missions. Observations of auroras and exospheres make atmospheric, plume, and internal activity remotely observable (see Chapter 3). The observatories may well provide key measurements of the composition of the Galilean moons that have been difficult to characterize from Galileo data. These observatories can provide monitoring and characterization of known ocean worlds, such as Neptune's Triton, and search for evidence of oceans within the moons of Uranus. In addition, such facilities can search for evidence of putative ocean worlds within the Kuiper Belt and Oort clouds, for which few detailed observations are in hand, and which could motivate future spacecraft missions.

While no current missions to the moons of Uranus or Neptune under development by NASA, the science of these bodies is a major driver of interest in the Ice Giant systems (see, for example, Hofstadter and Simon 2017). Moreover, a better understanding of the solar system's Ice Giants will help us understand the hundreds of Neptune-sized exoplanets detected by Kepler and other facilities. While Saturn's moons Rhea, Dione, and Mimas may be ocean worlds, Neptune's Triton almost certainly is and, as such, is a particularly promising target for future missions to the outer solar system. With a dynamically changing surface (e.g., Bauer et al. 2008) including the first detection of cryovolcanism in the solar system from the 8 km methane geysers (e.g., Kargel 1995), Triton appears to be resurfacing, and with little topography observable, an ocean below its ice shell is strongly suspected. Moreover, as a captured Kuiper Belt Object, Triton is an archetype of potential ocean worlds like Pluto in the far reaches of the solar system. Thus, the Outer Planets Assessment Group (OPAG) Roadmap for Ocean Worlds suggested prioritizing Neptune, due to the potential habitability of Triton. With an Ice Giant mission advocated as a high priority mission within the 2013 *Visions and Voyages* planetary science decadal survey, the potential selection of such a mission could accelerate ocean worlds science in the coming decades. Similarly, a return to Pluto, or dedicated ocean moons missions made possible by open New Frontiers calls in future opportunities could expand greatly the number of known and characterized oceans within the solar system.

ASTROBIOLOGY GOALS FOR EXOPLANET MISSIONS

The next 20 years promise to revolutionize the field of exoplanet astrobiology, providing the first observations of habitable zone terrestrial planets and starting the search for life beyond the solar system. We will explore the environments of terrestrial planets orbiting M-dwarf stars, which likely undergo a very different evolutionary path than planets in the solar system. The nature and habitability of these alien worlds will be a key step in understanding the probability of life in the universe. Future direct imaging missions would allow us to probe to the surface environments of terrestrial planets orbiting stars like the Sun to search for oceans and signs of life. The committee has identified five key exoplanet research questions to be addressed over the next 20 years. Key research areas will include the formation of habitable planets, and the interactions between planet, star and planetary system, and the impact of these processes on exoplanet habitability.

- *Formation of habitable planetary systems*—How do habitable planetary systems form and what are their architectures?
- *Factors influencing habitability*—What are the characteristics and processes that affect planetary habitability?
- *Evolution of terrestrial planets*—How do terrestrial planets evolve around different stellar types?
- *Nearly habitable exoplanets*—Do nearby stars host habitable planets?
- *Life on other planets*—Is there evidence of life on other planets?

Below, we provide a description of the key research goals and enabling missions and technologies needed to answer these questions.

Formation of Habitable Planetary Systems

How do habitable planetary systems form and what are their architectures? Developing an overall picture of the planet formation processes that can lead to habitable exoplanets continues to be a key goal in astrobiology research. Obtaining statistics of exoplanetary systems can not only illuminate how common potentially habitable planets are, but also how the planetary architecture (the types and orbits of other bodies in the system) can impact the potential habitability of a terrestrial planet. To address the galactic prevalence of potentially habitable exoplanets, definitive constraints on the number of low mass planets as a function of stellar type, distance, radius, and mass are needed. To better understand the impact of the planetary system architecture on potentially habitable planets the overall architecture of systems with potentially habitable planets are needed. Improved statistics on demographics, the number and distribution of different types of planets (as seen Figure 6.1) will enable stronger tests of terrestrial planet formation models. Dynamical simulations can probe possible migration pathways that lead to final system architectures that may impact habitability. Observations of protoplanetary and debris disks are needed to provide a picture of planet formation and help identify volatile reservoirs and volatile transport throughout the early disk environment.

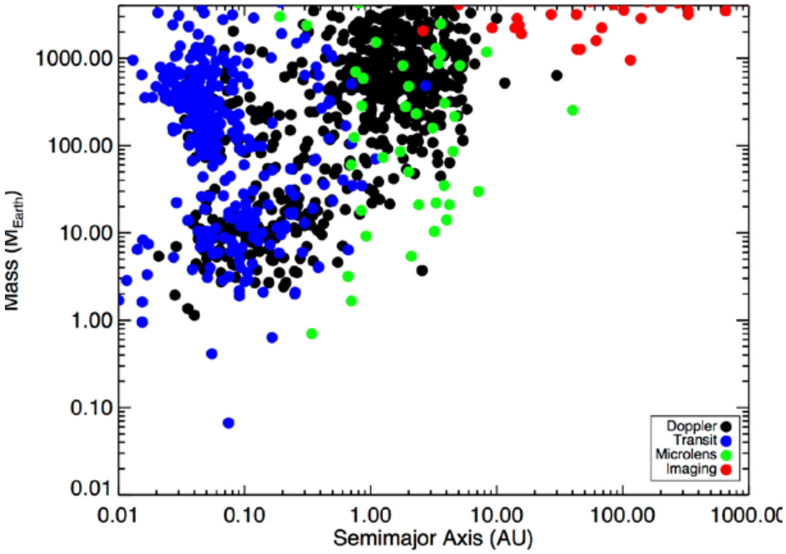

FIGURE 6.1 The current demographics of the measured masess and orbital separations of discovered exoplanet systems identified by detection method.

Factors Influencing Habitability

What are the characteristics and processes that affect planetary habitability? A planet's habitability is a complex interplay between intrinsic planetary processes, such as interior evolution, outgassing, magnetic field strength and atmospheric composition. The planet's habitability is also impacted by its interaction with the host star, both radiatively and gravitationally, via atmospheric escape, climate and photochemistry, and via orbital and tidal evolution. The planetary system, including the presence of sibling planets, also impacts habitability by enabling or inhibiting volatile delivery, and inducing orbital evolution. Key research goals in the next 20 years for planetary habitability will involve synthesis of modeling, observations and laboratory work to understand how the interactions between planet, star and planetary system impact planetary habitability, and how these processes and planetary habitability evolve dynamically over time. This knowledge will be needed to improve our ability to vet and rank potentially habitable planets for follow up, helping us identify those planets that are more likely to be habitable and harbor life.

Evolution of Terrestrial Planets

How do terrestrial planets evolve around different stellar types? The recent discovery of likely terrestrial size or mass planets orbiting nearby M-dwarf stars has opened up a new era of comparative planetology that will allow us to better understand the diversity of evolutionary paths for terrestrial planets. While Venus and Earth provide evidence of strongly divergent evolutionary paths for similar mass planets, understanding how planets can acquire, retain or lose habitability will be better informed with observations of a range of terrestrial planet atmospheres. Whether observations of terrestrial exoplanets reveal habitability or not, assessment of the planet's characteristics, and its interactions with other components of its planetary system, including the host star, will help elucidate those processes that can enhance or reduce a planet's habitability. A large set of observations of possible terrestrial planet environments will provide a baseline for interpretation of environments and potential biosignatures. For example, ocean and atmospheric loss has been posited as a means to generate extremely large amounts of atmospheric oxygen abiotically (Luger and Barnes 2015), but it is unclear how long this oxygen would persist in a planetary atmosphere against atmospheric, surface, chemical, and even magma ocean loss processes (Schaefer et al. 2016). Observations of a range of terrestrial exoplanetary atmospheres under different levels of stellar insolation and for stars of different ages will help constrain the likelihood of ocean loss as a potential false positive. Indeed, because the host star has a significant impact on planetary habitability, and the star's activity and luminosity evolve considerably, it will be important to determine and observe stellar activity indicators in systems of all ages and to understand evolutionary pathways, particularly for M-type stars, to feed back into the overall picture of the evolution of habitable terrestrial planets.

Nearly Habitable Exoplanets

Do nearby stars host habitable planets? Another key science goal in the next 20 years will be identifying nearby potentially habitable exoplanets, and determining whether they are habitable. While several promising candidates have been found, including TRAPPIST-1 e, f and g (Gillon et al. 2017; Anglada-Escudé et al. 2016) (Figure 6.2), Proxima Centauri b (Figure 6.3), and LHS 1140 b (Dittmann et al. 2016), larger numbers of targets will be needed to constrain the probability of habitability and to better understand the diversity and distribution of habitable environments. In the near term, the question of the habitability of M-dwarf planets will be a major theoretical and observational goal, as it is both observationally more tractable than observing planets orbiting sunlike stars, and more statistically significant for understanding the distribution of habitable planets in the galaxy. Terrestrial planets, which are small, are more readily observed and characterized when orbiting small M-dwarf stars, and yet M-dwarf stars, although the most common type of star in the galaxy, present many challenges to habitability for their planets. To understand whether these planets are habitable will require a coordinated effort between modelers and exoplanet and stellar observers to determine if M-dwarf planets can retain their atmospheres and oceans, and to understand the composition of M-dwarf planet atmospheres. In the longer term, observations of planets orbiting more sunlike stars, including true Sun-Earth analogs will extend our understanding of habitability to different stellar types, and provide a direct comparison with the Earth. To make the best determination of habitability possible, improved capabilities and techniques will be needed to study not only a planet's upper atmosphere, but also the planetary surface and near-surface atmosphere. As transit spectroscopy cannot do this, and direct imaging of exoplanets will be required. Larger sample sizes will also be valuable to provide an increased chance of finding a habitable environment, or placing more stringent limits on the dearth of habitable environments in the galaxy.

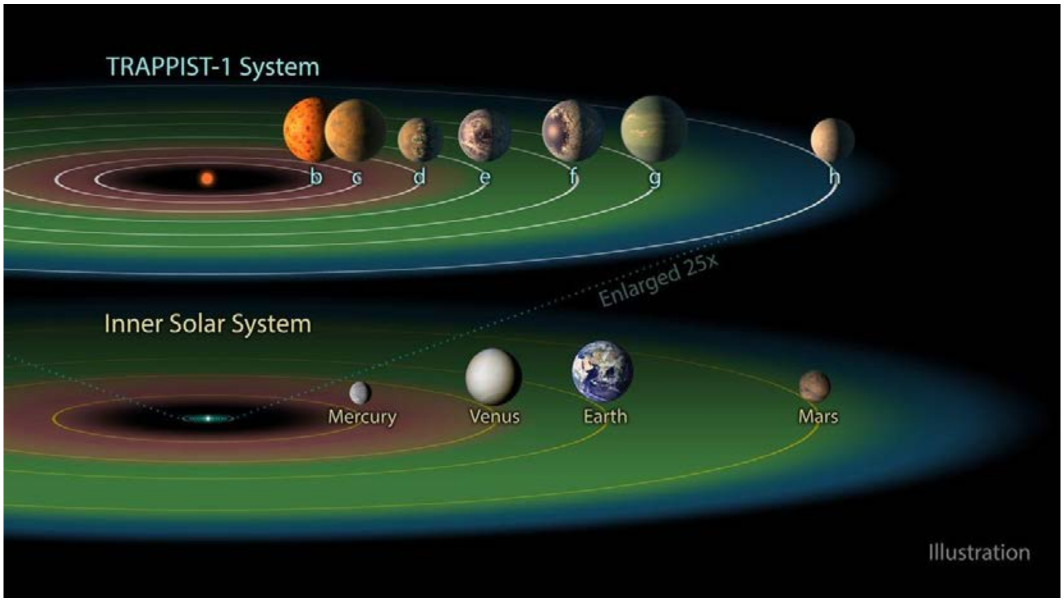

FIGURE 6.2 Illustration of the seven planets orbiting the TRAPPIST-1 ultra-cool low mass star (M8V). Planets e, f, and g orbit in the suspected habitable zone (green) based on the spectral type and modeling of the system. Note: the size of the planets is greatly exaggerated compared to their orbital radii and that the radial dimension of the TRAPPIST-1 system has been enlarged by a factor of 25. In other words, the entire TRAPPIST-1 system would fit well inside the orbit of Mercury. SOURCE: NASA/JPL-Caltech.

Life on Other Planets

Is there evidence of life on other planets? In the near-term, the search for signs of life will start with a handful of known habitable-zone planets orbiting M-dwarfs, but the longer term goal will be a more thorough survey of many more planets across a range of stellar types. To increase the chances of success in the search for life, research to support the interpretation of any potential biosignature observed needs to be undertaken. An important aspect of this research is the identification of new potential biosignatures, and efforts to increase the robustness of the interpretation of a potential biosignatures in the context of the planetary and stellar environment. A key specific research goal includes the identification of novel biosignatures, including agnostic biosignatures that are not tied to a known metabolism. Another goal is to understand, for new and existing biosignatures, how to best characterize a planet's environment and host star to assess the potential for both false positives and false negatives, and to recognize the observational markers of key stellar and planetary characteristics that can be used to rule out false positives or negatives.

Pathways to Search for Life Beyond the Solar System

To address the key science goals and questions outlined above, advances in interdisciplinary interactions will be needed to leverage expertise from planetary science, astronomy, oceanography, chemistry, and biology to address habitability as the outcome of the dynamic interaction between planet, star and planetary system. These efforts to explore planetary environmental parameter space will enable identification of the most promising targets for biosignature searches, and guide the observation plans for upcoming ground- and space-based observations (Table 6.1). To complement these theoretical efforts ground- and space-based observational facilities will expand our knowledge of exoplanet demographics, refining estimates of the prevalence of habitable zone planets, and identifying nearby targets for exploration.

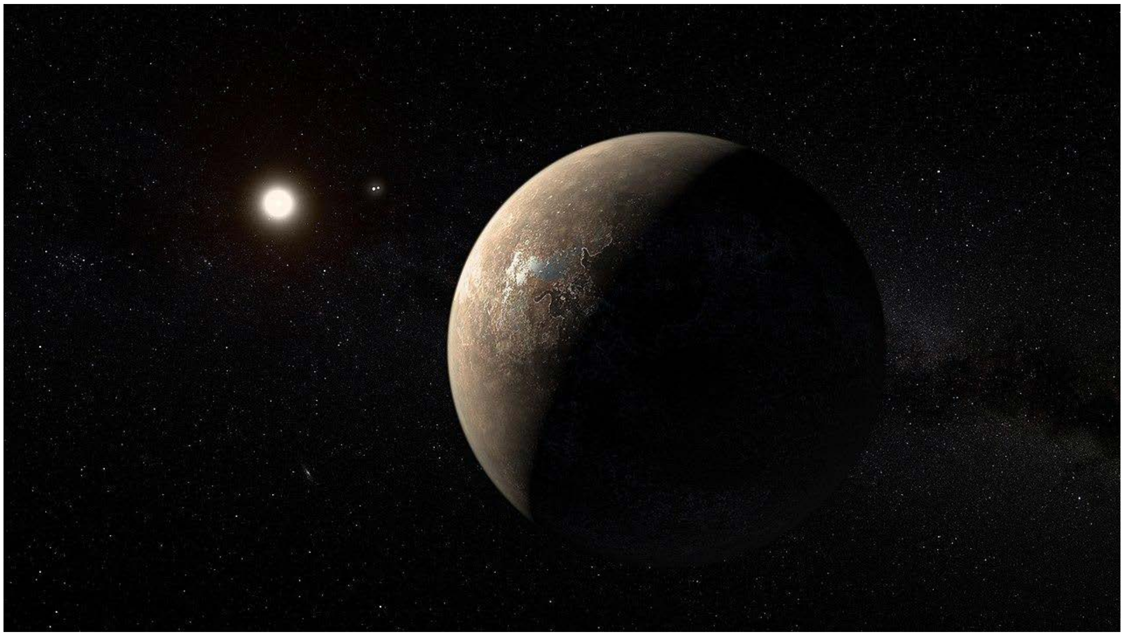

FIGURE 6.3 Artist rendition of the Proxima Cen b, a possibly rocky planet orbiting the red dwarf Proxima Centauri and the Alpha Centauri binary in the distance. SOURCE: ESO/M. Kornmesser.

Starting in the 2020s, ground-based facilities and NASA's JWST will obtain the first observations of habitable zone planets orbiting M-dwarfs using high-resolution and transmission spectroscopy that will address questions on the nature and habitability of the most common type of habitable zone planet in the galaxy. This activity will also provide an observational test of the habitable zone concept. Specific observational goals will be to ascertain if terrestrial exoplanets can retain an atmosphere, and if so, the diversity of these atmospheres and their implications for planetary habitability and life. In the 2035 timescale, all three giant segmented mirror telescope (GSMT) programs have planned second generation instruments that will be capable of direct imaging of terrestrial planets as well spectroscopic capabilities for exploring biosignatures. A large space-based direct imaging facility will be capable of searching for oceans on terrestrial exoplanets and of surveying a statistically significant sample of habitable terrestrial planets.

Over the next two decades a variety of large and small-scale space missions, ground-based observatories, and new technologies are being developed that will be capable of addressing core astrobiology exoplanet questions. Subsequent sections address a selection of key activities.

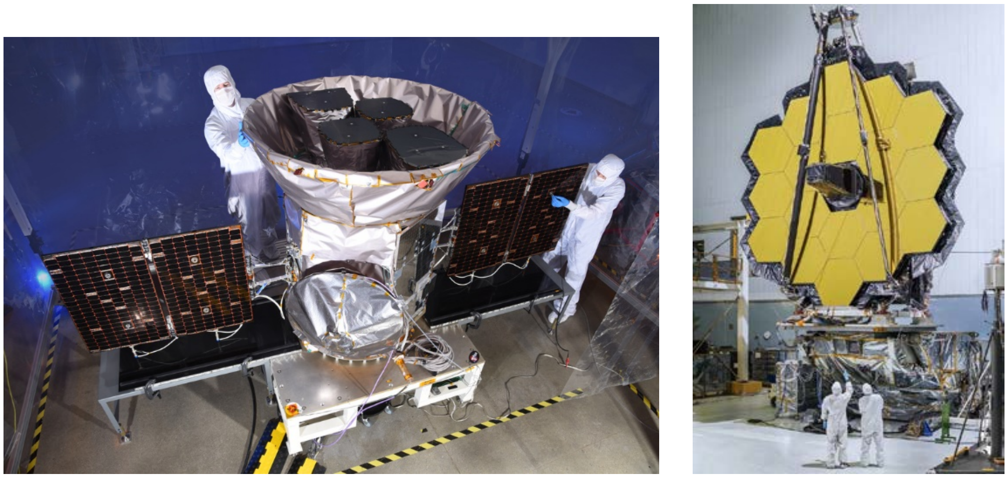

FIGURE 6.4 (Left) The Transiting Exoplanet Survey Satellite (TESS) being assembled at NASA Kennedy Space Center in Florida. (Right) The James Webb Space Telescope (JWST) primary mirror and folded secondary mirror at NASA Goddard Facility getting ready for testing. SOURCE: Left: Orbital ATK. Right: NASA/Chris Gunn.

The Transiting Exoplanet Survey Satellite (TESS; 2018-2020)

TESS (Figure 6.4) was successfully launched in April 2018. It will perform an all-sky survey, searching for transiting planets orbiting stars that are much closer to the Sun than the very distant targets surveyed by the Kepler space telescope. TESS will obtain high-cadence lightcurves of 200,000 nearby bright stars to search for transiting planets amenable to detailed follow-up observations. Though not designed as a statistical mission, the data collected by TESS will improve our knowledge of the demographics of short-period planets,

Nearby targets are more amenable to detailed follow-up observations that will reveal planetary characteristics and environments. TESS is anticipated to find ~15,000 new planets, a handful of which (~10) will be terrestrial-sized exoplanets orbiting in the habitable zones of M-dwarf hosts (Sullivan et al. 2015; Barclay et al. 2018). These latter targets can be prioritized for observation with the Ariel, James Webb Space Telescope (JWST; see below) or with ground-based Giant Segmented-Mirror Telescopes (GSMTs; see below). TESS will also place definitive constraints on the number of short-period planets as a function of stellar type, distance and radius. Obtaining masses for these planets will rely on support from ground-based telescopes capable of deriving planetary masses using radial velocity (RV). The masses, when combined with the sizes determined from transit, will provide crucial constraints on planetary bulk composition, which is needed to determine if these planets are likely to be terrestrial. As such, the availability of RV support is a primary means to maximize the science return from TESS and to optimize selection of those planets most likely to be habitable for further observation. Statistical data from TESS's and ESA's Gaia astrometry mission will also provide information on overall planetary architecture, especially when coupled with radial velocity monitoring or direct imaging that can detect additional more distant or non-transiting planetary companions. Improved demographics with robust statistics will enable stronger tests of terrestrial planet formation models.

James Webb Space Telescope (JWST, 2021-2026)

JWST (Figure 6.4) will provide our first chance to assess terrestrial exoplanet habitability and search for signs of life on planets orbiting M-dwarf stars (Meadows et al. 2018). JWST observations using transmission spectroscopy in the visible and near-infrared, as well as secondary eclipse and phase curve observations at thermal wavelengths, can be used to search for the presence of a high-molecular weight (e.g., oxygen or carbon dioxide) atmosphere. If such is confirmed, JWST can also be used to search for atmospheric gases, including biogenic ones (Schwieterman et al. 2016), in a planet's upper troposphere and stratosphere. Highly-irradiated terrestrial planets close to their star will be the most easily observed, but in favorable cases, some potentially habitable planets such as TRAPPIST-1e, may be probed, albeit with several hundred hours of exposure time (Meadows et al. 2018). Thermal observations using secondary eclipse can be used to determine planetary temperature, and to search for atmospheric gases. For non-transiting habitable zone planets such as Proxima Centauri b, thermal phase curves may reveal day-night temperature contrasts that indicate whether or not an atmosphere is present (Kreidberg and Loeb 2016), and molecules can also be sought using these observations. Because transmission spectroscopy is likely more sensitive than secondary-eclipse emission spectroscopy, the former will be the preferred mode of characterizing habitable-zone planets with JWST. However, this technique will not be able to observe the planetary surface or probe the near-surface atmosphere, making habitability assessment more challenging (Meadows et al. 2018).

More generally, JWST will help us better understand the evolution of terrestrial planets orbiting M-dwarfs, including putting constraints on atmospheric and ocean loss processes, and potentially providing an observational test of the habitable zone concept via observations of the 7 planets spanning the habitable zone in the TRAPPIST-1 system. In the process it will also teach us about the variability of M-dwarfs at near-infrared wavelengths, and about observations required to interpret exoplanet data taken by JWST and ground-based telescopes. Mid-infrared spectroscopic measurements of young disks with JWST also have the potential to identify the signatures of volatile elements as a function of radius. Mid-infrared spectroscopic measurements of forming stars with JWST also have the potential to identify the signatures of volatile elements as a function of planetary separation. The combination of moderate spectral resolution with the high spatial resolution of JWST offers the ability to map pre-stellar cores, protostars, and young disks down to the regions where planet formation is thought to occur. This wavelength range will allow for spectroscopic measurement of the precursors of organic molecules and ices.

Current Large Ground-Based Facilities (2018-2025)

Upcoming instrumentation and surveys on existing ground-based facilities will be able to expand the demographic discovery space (Figure 6.1) of terrestrial planets around solar-like stars and less massive K and M-stars. The high-resolution Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) on the Very Large Telescope (VLT) will begin radial velocity surveys in late 2018, and is projected to have a Doppler precision capable of detecting Earth-mass planets around the HZ of solar-type stars (Hernandez et al. 2017). The Keck Planet Finder (KPF) is the next generation high resolution fiber-fed spectrograph that is currently being developed for Keck Observatory to conduct high-precision radial velocity exoplanet measurements (Gibson et al. 2016). The higher signal-to-noise afforded by 8-10m diameter telescopes (compared to their 4m-class counterparts) with ESPRESSO and KPF will be also able to probe radial velocities of fainter stars and continue to expand our understanding of planetary architectures and formation.

Direct imaging capabilities using coronagraphs and extreme adaptive optics, like the Gemini Planet Imager and SPHERE, are now being further developed for new instrumentation programs in the coming decade. These next generation direct-imaging instruments on 8-10m class telescopes will be essential for technology development that will feed into the future GSMTs. Observations of planets in star forming regions with non-redundant masking on 8-10 meter class telescopes have the opportunity to show ongoing accretion of large planetary companions, providing hints of formation and volatile transport occurring throughout natal disk environments. Detecting the light from nearby systems like Proxima Centauri b and potentially new nearby planetary systems discovered by TESS will become prime, though exceedingly difficult, targets for 8-10m direct imaging cameras (Lovis et al). The VLT spectrometer and imager for the mid-infrared (VISIR) instrument is to be upgraded with new wavefront sensors and coronographic capabilities for direct imaging of planets in the Alpha Centauri system. In addition, instruments are currently being designed for near-infrared direct imaging coupled with high resolution spectroscopy using Keck Observatory with the Keck Planet Imager and Characterizer (KPIC; Mawet et al. 2017). Rapid technological development of infrared detectors, wavefront sensors, deformable mirrors, coronagraphs, and fiber-injection units now allow such test-bed systems to be built for 8-10m telescopes that will be capable of spectroscopy of low mass exoplanet atmospheres.

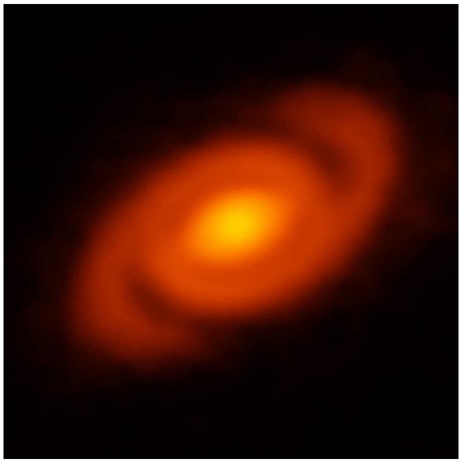

FIGURE 6.5 Spiral density arms observed with ALMA in the protoplanetary disk surrounding the young star Elias 2-27. SOURCE: B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO).

ALMA will continue to play a crucial role in characterizing both young and debris disks. Current observations of disks with ALMA have yielded a detailed array of morphologies and molecule measurements (e.g., Andrews et al. 2016; Pèrez et al. 2016). The structures seen in both young disks (Figure 6.5) and debris disks provide hints of possible planet formation in progress, as well as potentially signaling ongoing phase transitions that may play a key role in determining where planets form and what their atmospheres are made of. ALMA measurements are deeply probing the chemical processes in these disks, including the detection of complex molecules that could play a crucial role in pre-biotic chemistry (e.g., Oberg et al. 2015; Bergner et al. 2018). Continued studies with ALMA of a large variety of disks will aid in the understanding of disk chemistry as a function of spectral type and morphological evolution as a function of age, potentially yielding signposts of habitable planet formation. The proposed Next Generation Very Large Array (ngVLA) would complement ALMA’s capabilities by providing increased angular resolution and access to longer watelengths. The ngVLA, with baselines up to 60-times than those of ALMA and a 10-times greater sensitivity, will be proposed for prioritrization by the next astronomy decadal survey [1]

***WFIRST (2025-2035*)**

The WFIRST (Wide Field Infrared Survey Telescope) mission entered Phase B in May 2018, with a currently estimated launch in the late 2020s. The nominal mission decision calls for a coronagraphic instrument which will be used primarily to characterize the atmospheres of known Jupiter analogs detected via radial velocity using low-resolution spectroscopy. Simulations have shown that the mission could be photometrically sensitive to a few nearby super-Earth planets. The accomplishment of

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[1] For more information about the proposed ngVLA see http://ngvla.nrao.edu/pages/science.

these goals requires significant advances in space coronagraphic design, serving as a precursor to larger space missions to measure terrestrial planet atmospheres. Additional required developments include the advancement of spectral retrieval techniques and models for reflected light atmospheric measurements of Jupiters and super-Earths (e.g., Lupu et al. 2016). WFIRST is also designed to be compatible with a potential future starshade. Such a development would offer access to imaging Earth-like planets in nearby systems and would represent a critical technological leap for future missions.

FIGURE 6.6 The Giant Segmented Mirror Telescope (GSMT) projects from left to right: Giant Magellan Telescope (25 m); Thirty Meter Telescope (30 m); and European Extremely Large Telescopes (39 m). First light for these telescopes are predicted in 2028-2030, and all three programs are currently exploring 2nd light direct imaging capabilities of exoplanets. SOURCE: Left to right: Courtesy of GMT Corporation; TMT Observatory Corporation; ESO/L. Calçada/ACe Consortium.

Ground-based Giant Segmented Mirror Telescope (2028 - 2035)

The technological development occurring on current ground-based optical facilities is essential for the pathway of exoplanet and biosignature research using the future ground-based Giant Segmented Mirror Telescope (GSMTs) (Figure 6.6). There are three worldwide endeavors that aim to have a 25-40 m optical telescopes in operation by 2028-2030: the Giant Magellan Telescope (GMT) with a 25-m aperture at Las Campanas Observatory in Chile; the Thirty Meter Telescope (TMT) with a 30-m aperture at either Mauna Kea, Hawaii, or Roque de los Muchachos on La Palma, Spain; and the European Exteremely Large Telescopes (E-ELT) with a 39-m aperture on Cerro Armazones, Chile. The GMT first light instrument will be a high resolution spectrograph (Szentgyorgyi et al. 2016) that will be capable of measuring precision radial velocities of Earth-sized planets and of searching for atmospheric biosignatures, such as O_2. At first light, TMT and E-ELT will have near-infrared integral field spectrographs and imagers that will be capable of spectroscopically characterizing atmospheres of jovian-sized planets that are at large separations from their young host stars.

All three GSMTs projects are conducting conceptual studies and associated technology development activities with the goal of deploying second generation instrumentation that will have direct imaging and spectroscopic capabilities for exoplanet and biosignature studies.[2] The test-bed instrumentation and technological developments that are occurring on current 8-10m class telescopes and coronagraph designs are essential for reaping the benefits from GSMT direct-imaging capabilities. These second generation exoplanet instrumentations are currently being designed to use high dispersion coronagraphy techniques at near-infrared wavelengths, which have the potential of reaching the necessary 10^8 contrast and sensitivities for studying rocky planets around M-dwarfs and nearby stars. Near-infrared

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[2] Examples of concepts for second-generation instrument for the three GSMT projects underway include the following: the Planetary Camera and Spectrograph (PCS) for the E-ELT (see https://ao4elt3.sciencesconf.org/12804/document and https://spie.org/Publications/Proceedings/Paper/10.1117/12.2056842); the Planetary Systems Imager (PSI) for the TMT (see https://spie.org/Publications/Proceedings/Paper/10.1117/12.2314331 and https://spie.org/Publications/Proceedings/Paper/10.1117/12.2314173); and the Giant Magellan Extreme Adaptive Optics System (GMAGAO-X) for the GMT (see https://magao-x.org/gmagao-x/).

high-resolution spectroscopy coupled with this mode will allow the study of molecular species such as O_2, H_2O, CH_4, and CO_2 in these exoplanetary atmospheres. At mid-infrared wavelengths with coronagraphy, GSMTs will have the capability of directly imaging the thermal emission of rocky planets around nearby solar-like stars, and potentially with low spectral resolutions the ability to trace H_2O and CO_2.

Cubesats (2018-2023)

Complementing the much larger facilities and missions, Cubesats, nanosatellites of less than 10 kg mass, support relatively inexpensive missions with short development lead times, and can provide a nimble and flexible solution to specific science goals and technology demonstrations. Two Cubesat missions have been launched or funded that are relevant to astrobiology: The Arcsecond Space Telescope Enabling Research in Astrophysics (ASTERIA), which was launched in late 2017, and the Star-Planet Activity Research Cubesat (SPARCS), to be launched in 2021.

ASTERIA is designed primarily to demonstrate that a CubeSat can collect photometric data, and process photometric light curves. The mission's secondary goals include measurement of stellar rotation periods, characterizing the activity of exoplanet's parent stars, and providing simultaneous photometric measurements in support of ground-based radial velocity measurements.

SPARCS is a funded mission that will provide comprehensive measurements of the time-dependent spectral slope, intensity and evolution of M dwarf stellar ultraviolet radiation, including flare activity. These measurements are crucial to assess atmospheric retention and planetary habitability, and interpret atmospheric compositions and biosignatures for planets orbiting low-mass stars. SPARCS will monitor stellar activity in ~ 25 M-dwarf stars with ages spanning 20 Myr to 5 Gyr in two ultraviolet photometric bands simultaneously. These observations will help illuminate the evolution of stellar activity and the history of potentially habitable systems that may soon be the targets of biosignature probes. These observations can only be performed in space, and the ultraviolet-capable Hubble Space Telescope is a common-user facility that cannot support the dedicated observing campaigns required to monitor stellar activity over one to three stellar rotations. SPARCS will be capable of target of opportunity observations to support ultraviolet characterization of new habitable-zone planet host stars identified by TESS.

Space-based Next Generation Flagship Missions (2035 – beyond)

NASA is currently funding four concept studies for flagship missions to fly after JWST, and these missions will be ranked by the Astronomy Decadal Survey. They are: i) the Large Ultraviolet Optical Infrared Surveyor(LUVOIR),[3] a large aperture (8-15m) general observer facility that will be capable of direct imaging of exoplanets; ii) the Habitable Exoplanet Explorer (HabEx),[4] a smaller aperture (4-6m), more exoplanet focused direct imaging mission; iii) the Origins Space Telescope (OST),[5] a mid-infrared moderate aperture telescope that is a successor to JWST; and iv) Lynx, an X-ray Observatory.

The direct imaging missions, LUVOIR and HabEx (Figure 6.7), will have the capability of suppressing the light from the parent star and surveying up to hundreds of stars in the local solar neighborhood to search for habitable zone terrestrial planets. These missions will then be able to image and obtain direct imaging spectra of non-transiting terrestrial planets within the habitable zones of a handful to several dozen more Sun-like (F, G, K) stars. The larger aperture LUVOIR will also be able to directly image planets orbiting nearby M dwarfs. Consequently, these telescopes will allow the study of planets orbiting stars more like our own, and will complement what might have been learned by that point about M-dwarf planets by JWST and ground-based telescopes. These direct imaging observations will provide a significant increase in our capability of characterizing exoplanets for habitability and life by enabling an observational probe through the entire atmospheric column of a planet, as well as by direct

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[3] For more information about LUVOIR see https://asd.gsfc.nasa.gov/luvoir/.

[4] For more information about HabEx see https://www.jpl.nasa.gov/habex/.

[5] For more information about OST see https://asd.gsfc.nasa.gov/firs/.

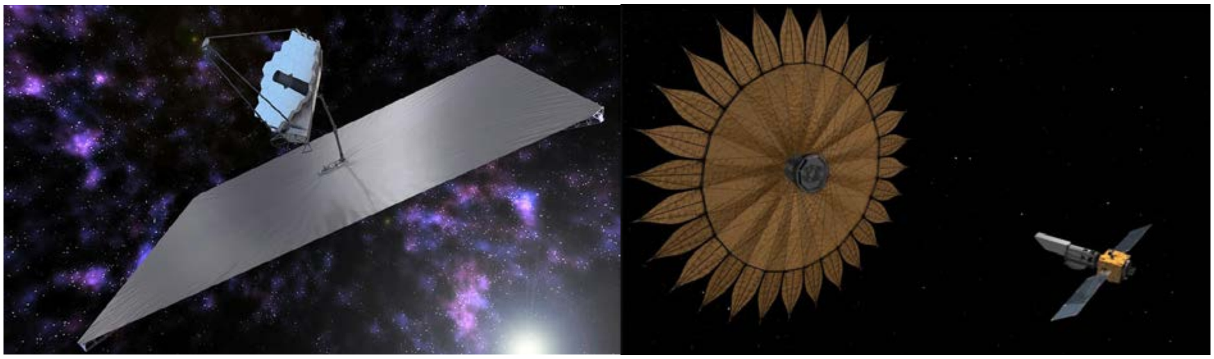

FIGURE 6.7 Development phases of proposed future space-based telescopes that are capable of directly imaging an Earth-sized planet in the habitable zone to potentially study biosignatures: Large Ultraviolet Optical Infrared Surveyor (left); Habitable Exoplanet Imaging Mission (right). SOURCE: (Left) NASA Goddard; (right) NASA Jet Propulsion Laboratory.

imaging of the planetary surface. Notably, direct imaging can be done for non-transiting planets, and thus can be used to search for planets around all of the nearby stars. This technique is more sensitive to near-surface water and biosignatures than are the transmission observations that will be obtained by JWST. Spectra will be obtained from 0.2-1.8 um by LUVOIR and HabEx. HabEx spectroscopic capabilities will increase if it is flown with a starshade, which would allow it to observe planets close to their star that would otherwise have been the purview only of LUVOIR. Transmission observations from the ultraviolet to the near-infrared are also possible with these telescopes. HabEx will explore the nearest stars to search for signs of habitability and biosignatures. LUVOIR, with its larger aperture, will survey more stars to constrain the frequency of habitability and biosignatures for up to 50 terrestrial habitable-zone exoplanets, and to enable enhanced comparative planetology and produce a statistically meaningful sample of exoEarths. Even if they do not find evidence for life, either mission would enormously increase our knowledge of terrestrial planet atmospheres by expanding the database beyond the four rocky planets in the solar system.

The Origins Space Telescope is currently conceived to be a general observer mid-infrared 6m telescope, similar to JWST. Like HabEx and LUVOIR, it will support a broader astrophysics community and will be capable of observing transits of terrestrial planets in the habitable zone of M dwarfs. Emission observations via thermal phase curves or secondary eclipse of transiting exoplanets may also be possible. Lynx will provide important observations of potential exoplanet host stars, helping to monitor stellar activity and the space radiation environment for habitable zone planets.

Synergies with Solar System Missions

In understanding terrestrial exoplanets, synergies will exist with solar system missions that seek to understand terrestrial planetary processes and the history of habitability on Venus and Mars. This relevance to the astrobiology of exoplanets is, in general, a bonus. That is, the relevance of the small subset of solar system missions discussed in this section to astrobiology is in addition to the primary science these missions were selected to undertake. While Venus, Earth and Mars likely formed from the same initial inventory of the solar nebula material, and isotopic and geological evidence has suggested that each planet supported surface liquid water in the past, their atmospheres and climates have diverged over the past 4 billion years. Comparative terrestrial planetology will help inform the processes that support, maintain, and destroy planetary habitability, helping us interpret habitable zone exoplanets. Missions to Venus like the currently flying JAXA *Akatsu*ki mission that take steps to improve our understanding of current processes like lightning and volcanism on Venus inform these processes. Future Venus missions that may also provide insights into the early evolution of Venus' atmosphere, the current outgassing rates, atmospheric escape, and photochemistry will provide clues to the runaway greenhouse process, and the evolution of atmospheres for highly-irradiated terrestrial exoplanets. Similarly studies of martian atmospheric loss processes by the MAVEN spacecraft at Mars have been used to inform calculations for atmospheric lifetime for terrestrial planets orbiting M dwarf stars, a key question in exoplanet habitability (Brain et al. 2017).

With the detection of exomoons on the horizon (Teachey et al. 2018; Rodenbeck et al. 2018), as well as the prevalence of possible water worlds around other stars, lessons learned from the ocean worlds of the solar system, including Earth, Europa, Ganymede, Enceladus, and Titan, will bear important information that can be integrated into exoplanetary missions. The Europa Clipper mission will measure the composition, environment, and geophysical characteristics of Europa along with its ocean. This mission, through gravity, may finally answer whether activity at the seafloor has ever occurred on this moon, an archetype for other ocean worlds. The JUICE mission will focus on Ganymede while also studying Jupiter, Europa and Callisto, and has as its central goal to understand the "emergence of habitable worlds around gas giants," directly feeding into exoplanet studies. Ganymede itself, as a planet-sized ocean world, is also an analog for other potential ocean worlds whose size is great enough to produce high pressure ice phases at the deep sea floor. JUICE will provide information on whether Ganymede can be considered habitable, and inform the exoplanet community on the range of exotic conditions experienced on ocean planets. Any Enceladus or Titan missions would provide similar context. Since the great observatories planned for the coming decades, both on the ground and in space, will observe the ocean worlds with the same instruments as we search for inhabited worlds beyond the solar system, such observations may prove complementary.

TABLE 6.1 Current and future technology programs and the measurements they will provide to address the key astrobiology questions for exoplanet research programs.

Key research and development goals over the next 20 years for pathways to search for life beyond the solar system					
Enabling technologies and techniques	**How do habitable planetary systems form and what are their architectures?**	**What are the characteristics and processes that affect planetary habitability?**	**How do terrestrial planets evolve around different stellar types?**	**Do nearby stars host habitable planets?**	**Is there evidence of life on other planets?**
Transiting Exoplanet Survey Satellite (TESS)					
Nearly all-sky precision relative photometry to detect transiting planets	Demographics of nearby exoplanetany systems for relatively short-period planets	Multi-planet systems, dynamical interactions	Demographics of terrestrial planets for a broad range of stellar host types.	Frequency of potentially terrestrial planets orbiting M dwarfs.	Identify optimal targets for JWST follow up to search for the potential habitability of terrestrial planets in the jhabitable zones of nearby, bright M dwarfs.-
James Webb Space Telescope (JWST)					
Transit spectroscopy	Atmospheric composition, volatiles	Variation of atmospheric composition of low-mass planets with planet mass, distance from star, and host star properties	Atmospheric composition for M dwarf terrestrial planets as a function of orbital distance.	Existence and composition of atmospheres for M dwarf terrestrials.	Search for biosignatures for a handful of M-dwarf habitable zone terrestrials.

Key research and development goals over the next 20 years for pathways to search for life beyond the solar system					
Enabling technologies and techniques	**How do habitable planetary systems form and what are their architectures?**	**What are the characteristics and processes that affect planetary habitability?**	**How do terrestrial planets evolve around different stellar types?**	**Do nearby stars host habitable planets?**	**Is there evidence of life on other planets?**
Secondary Eclipse and Thermal Phase Curves		Atmospheric composition, and day-night temperature contrasts for more massive planetary companions.	Atmospheric composition and day-night temperature contrasts for hotter and larger terrestrials.	Possible measurements of atmospheric composition via near- and mid-infrared spectroscopy for a handful of M dwarf habitable-zone planets.	Search for biosignatures for M dwarf planets.
High-contrast photometry and spectroscopy of protoplanetary disks	Disk demographics and composition of young stars and nascent planetary systems	Disk dynamics, volatile delivery	Variation of disk properties with stellar age and mass.		
Ground-based <10m facilities					
Precision radial velocities	Mass measurements, long-period planets	Architectures and dynamics of mult-planet systems	Detection, minimum masses, and orbits of low-mass, habitable-zone planets around nearby low-mass stars with a range of masses.	Detection of terrestrial planets around nearby low-mass stars and possibly Sun-like stars. Density, surface gravity of transiting M dwarf, habitable-zone terrestrials.	
High-contrast direct imaging with extreme adaptive optics	Wide planet statistics, young planetary systems	Multi-planet systems, direct detection of non-habitable-zone planets on wide orbits	Demographics of nearby planetary systems via direct detection as a function of stellar mass.		
High-resolution spectroscopy, with adaptive optics		Mass measurements for non-transiting planets.	Detection of atmospheric constituents for massive planets.	Potential detection of the atmospheres of a limited number of small planets around nearby stars.	Biosignature searches for very nearby habitable-zone, M dwarf planets.
Transit detection and monitoring	Long-term monitoring of transiting systems	Long-term monitoring of	Detection of low-mass planets	Detection of nearby habitable	

Key research and development goals over the next 20 years for pathways to search for life beyond the solar system					
Enabling technologies and techniques	**How do habitable planetary systems form and what are their architectures?**	**What are the characteristics and processes that affect planetary habitability?**	**How do terrestrial planets evolve around different stellar types?**	**Do nearby stars host habitable planets?**	**Is there evidence of life on other planets?**
	for planetary companions.	transiting systems for planetary companions.	(including terrestrial planets) around nearby low-mass stars.	zone planets orbiting the smallest stars.	
Sub-millimeter imaging	Protoplanetary disks, volatiles, ices				
Mini- and nano- satellites (CubeSat)					
Time-resolved photometry	Demographics of exoplanets	Stellar activity	Environments of exoplanets as a function of host-star mass and age, detection of transits of low-mass planets identified via radial velocities.	Stellar activity and ultraviolet photometry for M dwarfs as a function of stellar mass and age; mass, radius, and density measurements for transiting low-mass planets.	
Wide Field Infrared Survey Telescope (WFIRST)					
Direct imaging spectroscopy (Test-bed technologies)	Circumstellar disks, jovian planets	Volatile deliveries	Atmospheric characterization of jovian planets	With starshade, detection of habitable-zone terrestrials around a few bright stars.	
Microlensing	Planetary system demographics at orbital distances of > 1AU, including free-floating planets	Determination of the frequency of giant planets beyond the ice line.	Masses for stars and planets.	Improved estimates of frequency of habitable-zone terrestrials.	
Giant Segmented Mirror Telescope (GSMTs)					
High resolution spectroscopy(including radial velocities)			Stellar-activity indicators, and characterization. Planetary mass. Atmospheric composition of terrestrials in transmission and reflected light.	Planetary mass for habitable-zone planets from M dwarf to Sun-like stars. Atmospheric composition for M dwarf habitable-zone planets in transmission and reflected light.	Potential biosignatures for M dwarf planets

Key research and development goals over the next 20 years for pathways to search for life beyond the solar system					
Enabling technologies and techniques	**How do habitable planetary systems form and what are their architectures?**	**What are the characteristics and processes that affect planetary habitability?**	**How do terrestrial planets evolve around different stellar types?**	**Do nearby stars host habitable planets?**	**Is there evidence of life on other planets?**
Direct imaging and spectroscopy	Young planet observations, solar system analog jovian planets	Disk dynamics, multiplanet dynamics	Atmospheric characterization	Nearby reflected light habitable-zone planets (M dwarfs) or thermal imaging (G dwarfs).	Biosignatures for select targets*
Future space-based missions					
Direct imaging (ultraviolet, visible-near-infrared	High-spatial-resolution disk imaging, planetary demographics, planetary system architectures.	Orbits and atmospheric composition of ice and gas giants. Stellar ultraviolet characteristics.	Terrestrial atmospheric composition from direct imaging spectroscopy (Sun-like stars) and transmission spectroscopy (M dwarfs). Stellar ultraviolet characteristics for photochemistry, ocean and atmospheric loss.	Terrestrial atmospheric composition of habitable-zone terrestrials from direct imaging spectroscopy (Sun-like stars) and transmission spectroscopy (M dwarfs). Planetary rotation rate, photometric mapping, possible ocean detection (Sun-like stars).	Spectroscopic detection of biosignatures, false positives and other environmental context for G dwarf and other more Sun-like stars. Constraints on the frequency of living worlds for larger numbers of planets observed.
Extreme ultraviolet			Stellar characterization for planetary atmospheric and ocean loss.	Characterization of stellar variability for transit detection methods, stellar characterization for atmospheric and ocean loss, photochemistry.	
Mid- to far-infrared	Protoplanetary disk characterization		Transit spectroscopy of terrestrial M-dwarf planets. Emission spectroscopy and phase curves for terrestrial planets.	Transit spectroscopy of HZ M-dwarf planets	Transit spectroscopy of potential biosignatures for M-dwarf planets
Advancements in modeling techniques					
Planetary, Habitability and Biosignature Modeling	Planet formation modeling to constrain volatile delivery and initial terrestrial planet composition.	Interior/outgassing/ atmosphere models and stellar, orbital and planetary evolution models to predict properties of	Stellar, orbital, atmospheric evolution models to understand atmosphere and ocean loss and characterize	Evolution models to predict possible environmental states and coupled climate/photoche	Interdisciplinary modeling to develop a comprehensive framework for biosignature assessment in the

Key research and development goals over the next 20 years for pathways to search for life beyond the solar system					
Enabling technologies and techniques	**How do habitable planetary systems form and what are their architectures?**	**What are the characteristics and processes that affect planetary habitability?**	**How do terrestrial planets evolve around different stellar types?**	**Do nearby stars host habitable planets?**	**Is there evidence of life on other planets?**
		secondary atmospheres and the likelihood of a surface ocean.	planetary processes that could mimic biosignatures.	mical and radiative transfer modeling to predict observational characteristics for habitable-zone terrestrials.	context of the environment (incl. false positives and negatives).
NOTES: * assuming that direct imaging capabilities are being fed by a high-resolution spectrographs. This option is being explored for the TMT and GMT 2nd generation instruments.					

UNDERSTANDING BIOSIGNATURES IN THE CONTEXT OF THEIR ENVIRONMENT

Although significant progress has been made since publication of the 2015 Astrobiology Strategy, those advances have revealed that much more work needs to be done before the majority of biosignatures are well enough understood to resolve outstanding controversies regarding the earliest evidence of life on this planet, let alone on planets, moons or exoplanets beyond Earth. There is a pressing need for a comprehensive set of standards to guide the evaluation and testing of remote and in situ biosignatures in their environmental context and to take into account the probabilities of false positives, false negatives, and levels of uncertainty. Further, the range of potential biosignatures—both remote and in situ—is in need of re-evaluation to take into account extreme or even "weird" life. Given recent trends in biosignature research and detection technology, as well as gaps in existing knowledge, over the next 20 years the following questions will prove critical:

1. *Novel biosignatures*—How are novel biosignatures identified?
2. *Interpreting biosignatures*—How can confidence in the interpretation of biosignatures be increased?
3. *Detecting biosignatures*—Given preservation biases and false negatives, which biosignatures have the highest probabilities for detection?
4. *Achieving consensus*—How can biosignature detection and interpretation be standardized as a probabilistic outcome such that community consensus is achievable when a purported sign of life is detected?

Novel Biosignatures

How are novel biosignatures identified? The suite of in situ and remotely detectable biosignatures is at present modest and needs to be expanded. In particular, accelerated efforts to understand alternative chemistries or metabolisms and their likely impact on the environment are warranted. Microbial life on Earth uses a well-defined set of electron donors and acceptors, largely determined by their environmental availabilities (Falkowski *et al.* 2008; Falkowski 2015). On planetary bodies within the solar system, these chemistries have led to a wide variety of complex organic molecules that may be preserved in the lithosphere and can be detected directly, although issues of false negatives, false positives and differentiation with signatures produced by non-biological processes remain a critical challenge.

Methods exist to compute the energy yields of redox reactions, even those reactions not known to be used by terrestrial life (Amend and Shock 2001). The caveat is that knowledge of in situ temperatures and concentrations of redox compounds is essential to enable meaningful evaluation of these potential metabolic drivers, and an understanding that the reactions lead to gaseous signatures is desirable. Novel biosignatures of metabolism may also be identified by studying metabolic processes on Earth in more detail, both by exploring Earth's past to identify when these processes became sufficiently pervasive to provide an environmental context for the biosignature (Magnabosco *et al.* 2018), and by surveying alternative redox partners that plausibly could be produced by life. For remote-sensing biosignatures, it is important to identify means by which life's complex interaction with its environment can be identified at a planetary scale, for example via atmospheric (gases and aerosols), surface, or temporal processes (day-night and seasonal processes).

While identification of biosignatures from specific known or past metabolisms can profitably continue to be pursued for both in situ and remote-sensing biosignatures, it will also be important to expand our understanding of agnostic biosignatures which identify complexity in the environment that is unlikely to have been produced by non-biological processes. For in situ life searches, examples include molecules with a sufficiently large number of steps required for their formation that they are unlikely to occur via abiotic processes (Marshall et al. 2017). Considerable work will be needed to extend this approach to remote biosignatures, but examples include global-scale complex chemical networks that are unlikely to have arisen by chance, or chemical disequilibria in planetary atmospheres that signify surface fluxes that are unlikely to be due to geological or photochemical processes alone.

Interpreting Biosignatures

How can confidence in the interpretation of biosignatures be increased? Equally important as the discovery of new biosignatures is the need to increase confidence in existing biosignatures. In part, this confidence will stem from an ability to identify false positives and false negatives, and to determine complementary measurements to rule them out, or to identify multiple lines of evidence to strengthen the conclusion that a given phenomenon or product is indeed due to life. Additionally, understanding the variety of environmental contexts that can either strengthen or weaken biosignature credibility will be crucial. The following are identified as gaps in present understanding, each of which will require further research:

- Following the template for biosignature assessment set by false positive studies for abiogenic oxygen (Meadows et al. 2018; Catling et al. 2018), identification of geological, photochemical, and other planetary processes for production, and quantification of likely fluxes, for abiogenic methane, nitrous oxide, methyl chloride, and other biosignature gases.
- Laboratory, field, and modeling studies that help to understand isotopic fractionation in both biological and non-biological systems;
- Analysis of biogenic sedimentary fabrics and their abiotic mimics; and
- Recognition of abiogenic processes that can mimic microscopic "cellular" objects, sedimentary fabrics, biomineralization, bioalteration, isotopic signatures and complex spatial organization of molecules.

Detecting Biosignatures

Given preservation biases and false negatives, which biosignatures have the highest probabilities for detection? False negatives that occur due to obfuscation or destruction of biosignatures provide an equally difficult and important challenge to address. Compounding the effect of physical and chemical processes that may reduce the signal of a biosignature to the lower limit of detection, preservation biases may alter or entirely erase the signature. Current gaps in understanding of false negatives and preservation biases include:

- Suppression or buffering of the rise in atmospheric concentrations of oxygen and other potential remote-sensing biosignature gases due to geological and surface processes.
- Recognition of environmental parameters that can alter remotely-sensed biosignature gases, especially those due to star-planet interactions or the effect of aerosols; which may ultimately influence target exoplanet selection;
- Alteration of biogenic gases that are encapsulated in ices or minerals;
- Degradation of mineralogic and isotopic signatures;
- Environmental perturbation of isotopic fractionation, especially when abiotic reactions do not proceed to completion;
- Destruction of materials by ionizing radiation, ultraviolet light, heat, pressure, tectonism, and water chemistry;
- Alteration of organic molecules, microscopic structures, and sedimentary fabrics due to mineral encapsulation, chemical modification, or aqueous delivery of silica, salts, sulfides, or chemical reducing agents; and
- Low-energy environments, with barely perceptible biological activity that would be difficult to detect above the baseline signal of abundant abiogenic processes. Such environments are prevalent in Earth’s subsurface and at the surface (e.g., Wilhelm et al. 2018).

Achieving Consensus

How can biosignature detection and interpretation be standardized as a probabilistic outcome such that community consensus is achievable when a purported sign of life is detected? The potential value of a biosignature for life detection derives from a combination of the above considerations and a comprehensive framework for biosignature assessment. It reflects not only the intrinsic value of the biosignature, but also the associated propensity for both false negatives and false positives, which together create an uncertainty and likelihood for detection unique to each biosignature. As a result, without standard assessment criteria and uncertainty calculations by which to evaluate each biosignature, it is difficult for the scientific community to agree upon the robustness of a biosignature interpretation, even when the environmental context and multiple lines of evidence integrated. As discussed in Chapter 4, this ambiguity can affect interpretations of potential biosignatures, as amply demonstrated by enduring controversies concerning the geologic and life record of early Earth. Resolving such ambiguities will require the development of comprehensive, probabilistic frameworks for the assessement for all newly proposed and existing biosignatures (e.g., Catling et al. 2018; Walker et al. 2018). Studies of biosignatures in the rock record of early Earth provide an ideal initial test bed for the development and “field testing” of biosignature criteria, standards, and uncertainties to facilitate consensus within the biosignature community when signs of life are detected on other planets.

Pathways to Standardizing Biosignature Interpretation and Uncertainty

Methods employed in the standardization of biosignature assessment and uncertainty have the potential to provide an objective path forward in the search for life beyond Earth. In the coming years, there is an urgent need to develop standardized methods for assessing the predictive value of biosignatures. This does not mean focusing solely on biosignatures that pertain to terrestrial organisms. That approach, although most readily undertaken, would risk false negatives by ignoring the possibility of life unlike our own. Stated more aspirationally, there is value in pursuing agnostic biosignatures that pertain to life in a more general sense, while keeping in mind the need to avoid false positives that may result from being too general. The challenge for biosignature science is to strive for a comprehensive, quantitative foundation that uses multiple lines of evidence and environmental context to provide the most robust life detection framework involving interdisciplinary laboratory, field and modeling work, as well as community efforts to develop a consensus on assessment to apply to the search for life beyond the Earth.

Biosignature Searches in the Solar System

Missions to Mars, Venus and the ocean worlds will provide opportunities to search for biosignatures, and provide insight into the planetary processes that may also lead to biosignature false positive and negatives. Besides Earth, Mars has been studied in greatest detail amongst terrestrial worlds, considering that it had the potential to sustain microbial life in the past, and could still have, contingent on liquid water in the martian subsurface as recently reported for the base of the martian polar caps by MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) (Oresei et al. 2018). Though detection of organics, in particularly recent confirmation of methane in the atmosphere (Webster et al. 2015, 2018) and organics in ancient mudstones (Freissinet et al. 2015; Eigenbrode et al. 2018) of Mars have been made with the Curiosity Rover, the data are inconclusive as to their origin. The Trace Gas Orbiter (TGO) of ESA’s ExoMars Program, which is entering its scientific phase, is designed to map the distribution of methane on Mars, and if possible its temporal and spatial variability. TGO will also measure other related trace gases. Though life as we know it generates methane, so that nearly 95% of methane on Earth is biological in origin, existing data for Mars do not reveal its origin. The TGO type of data are crucial for beginning to determine whether methane on Mars is biologic or geologic in nature, and whether it was produced only in the past and stored, or is being produced even today in the subsurface where liquid water may be present and water-rock reactions on-going. As on Mars (and Earth), methane is a key biomarker for habitable exoplanets. Besides methane, a number of other potential biomarkers including oxygen (or ozone, as proxy for oxygen), nitrous oxide, etc. as well as environmental context are essential to make an unambiguous claim of life on a habitable exoplanet.

The 2020 ExoMars lander/rover is equipped with a drill to access samples from up to ~1.5 meters depth, which is below most of the depth of penetration of galactic cosmic rays, thus increasing the chances of finding well-preserved organics, complementing Curiosity, which can drill down to only ~6 cm. ExoMars measurements may reveal the origin of the martian organics. Mars 2020 rover will cache samples for later return to Earth by a sample-return campaign (Box 6.1), allowing in depth investigation of martian rocks.

As a highly-irradiated terrestrial planet Venus can provide clues to several key photochemical and catalytic processes that affect the abiotic formation and destruction of O_2 in terrestrial planetary atmospheres. Future Venus missions that focus on atmospheric chemistry, as well as ongoing work on modeling Venus photochemical processes may provide important insights into the environmental processes needed to interpret any detection of O_2 in an M dwarf planetary atmosphere.

BOX 6.1
Mars 2020 and Sample Return

The Mars 2020 mission, which will investigate a landing site for possible biosignature preservation in full geologic context, is just 2 years from launch and, therefore, a detailed treatment of the mission itself is beyond the scope of this report. However, two aspects of the baseline mission are especially relevant to the charge given to this committee:

- The Mars 2020 rover (Figure 6.1.1) will collect and cache samples for possible return to Earth in the future and,
- The mission provides numerous opportunities for international collaboration and co-operation, and other astrobiological partnerships, as discussed in Chapter 7.

A Mars sample-return campaign is envisaged as a series of three sequential spacecraft missions that: first, collect and cache samples (i.e., Mars 2020); second, retrieves the cached samples and transports them to a stable orbit about Mars; and third, collects the samples from Mars orbit and returns them to Earth. If successful, the return of Mars samples to Earth for study in terrestrial laboratories will realize one of the top-level astrobiology goals identified in the 2007 NRC report, *An Astrobiology Strategy for the Exploration of Mars*, and the highest priority solar system science goal identified in the 2011 *Vision and Voyages* planetary science decadal survey.

The 2007 report stated that, “the greatest increase in understanding of Mars will come from the collection and return to Earth of a well-chosen suite of martian surface materials. Given the Mars Exploration Rover experience and current understanding of the nature of materials on the martian surface, a “grab sample” obtained from a stationary lander is not likely to be sufficient to provide the necessary data.” Furthermore, sample return was identified as a program that NASA and the Mars science community could begin in the near future and in a stepwise manner. The stepwise, or campaign approach was seen as less risky than a single, exceptionally complex mission that would also most likely be prohibitively expensive.

The 2007 and 2011 reports discussed the limits and advantages of in-situ sample analyses compared to what was achievable in Earth-based laboratories. These points are still relevant today and perhaps more so. The capabilities for in-situ instruments cannot ever be expected to match the range of techniques or the sensitivity, accuracy, and precision of those available in Earth-based laboratories. Earth-based sample preparation methods have achieved much greater significance in the search for molecular biosignatures now that the reactive and oxidizing nature of martian rocks has been confirmed by the results of the *Curiosity* rover mission. The astonishingly improved knowledge of diverse stable and radiogenic isotopic systems, and technologies for making measurements of them in Earth-based laboratories, will be informative about Mars environmental evolution, provide constraints on chronologies. These are areas where returned samples can yield insights and perspectives that are not possible with in situ sample analyses.

Phasing the campaign over at least three launch opportunities allows for early incorporation of inevitable improvements in spacecraft technology including communication and navigation systems, entry, descent and landing methodologies, and day-to-day operations. There will also be significant advances instruments for in situ evaluation of drilled samples, improvements in contamination control together with a much more sophisticated understanding of the martian regolith drawn from the experience with MSL and current orbiting spacecraft. Last, but not least, international interest and participation in a Mars sample return campaign means that such an expensive undertaking would be more realistic for the individual partners thereby allowing bold science objectives to be realized and planetary protection responsibilities (see Box 6.2) to be shared.

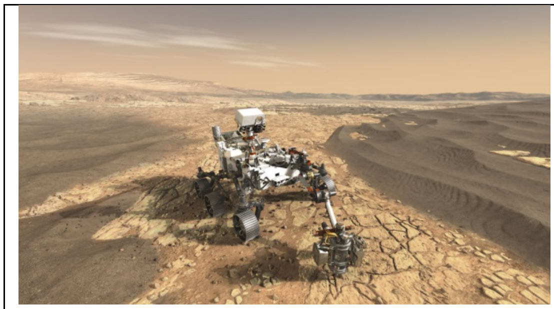

FIGURE 6.1.1 An artist's impression of NASA's Mars 2020 rover. SOURCE: NASA/JPL-Caltech.

BOX 6.2
Planetary Protection

Planetary protection protects solar system bodies from contamination by Earth life (forward contamination) in order to preserve the ability to conduct future origin-of-life and life studies at those destinations and protects Earth's inhabitants and environment from harm that could be caused by the introduction of extraterrestrial life (back contamination). The 1967 United Nations Outer Space Treaty (OST), to which the U.S. is signatory, states in Article IX that all states party to the treaty "shall pursue studies of outer space, including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination, and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." In addition, Article VI of the same treaty specifies that States Parties "shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities."

Technical aspects of planetary protection are developed through the Committee on Space Research (COSPAR), part of the International Council of Science (ICSU). International planetary protection consensus guidelines are developed through deliberations of the COSPAR Panel on Planetary Protection. Deliberations occur regularly with participants reporting new scientific findings with policy implications (e.g., water being more abundant at a particular target than was previously recognized), and raising questions regarding specific concerns (e.g., new activities in space exploration that could affect policy compliance). The Panel develops recommendations that the COSPAR Bureau may adopt for inclusion into the official COSPAR Planetary Protection Policy. Through this process, the COSPAR Planetary Protection Policy has evolved steadily and incrementally over the years since it was initially created. Spacefaring organizations such as NASA formulate and implement planetary protection policies and procedures that are consistent with COSPAR Planetary Protection Policy.

Recent years have seen significant developments in the exploration of planetary environments and understanding of the limits of life as well as new challenges in the development and implementation of planetary protection policies. A recent National Academies review of the planetary protection policy development process identified the following major challenges:

- Scientific and programmatic priorities for the robotic exploration of the solar system are increasingly focused on icy bodies of the outer solar system and the return of samples from Mars. The former present new challenges to the prevention of forward contamination because of the possibility that terran organisms may spread globally in a sub-ice ocean. The latter are of concern because martian samples are classified as "restricted Earth return", subject to strict containment until biohazard prevention protocols are satisfied.
- Human exploration of Mars presents challenges to current forward and back contamination policies and may require a wholesale reconceptualization of planetary protection regulations for Mars.
- The burgeoning space economy and possibility of private-sector robotic and human missions to Mars pose challenges to compliance with articles VI and IX of the Outer Space Treaty. These challenges are complicated by the absence of a regulatory body in the U.S. with authority to authorize and supervise private-sector activities beyond low-Earth orbit.

- The recent transfer of NASA's Office of Planetary Protection (OPP) from the Science Mission Directorate to the Office of Safety and Mission Assurance is generally regarded as a positive change. However, the move has had some negative consequences. The disestablishment of the Planetary Protection Subcommittee of the NASA Advisory Council has deprived the PPO of its primary internal source of independent scientific and technical advice. Further, the long-term future of the Planetary Protection research and analysis program, long underfunded and offered only intermittently in recent years, remains unclear.

Finding: Planetary protection is a promising area for increased public-commercial partnership, particularly in the areas of

- Researching sterilization techniques, which could benefit from developments in the pharmaceutical and food industries;
- Leveraging existing and future agency testing, assembly, and sterilization facilities, which may not be affordable to small commercial entities; and
- Ensuring adherence to consistent standards and best practices in planetary protection by public and private missions alike.

Biosignature Searches of Exoplanets

JWST and the ELTs will provide our first chance to look for signs of life on exoplanets, and search for false positives in highly-irradiated terrestrial atmospheres, including for JWST the possible detection of O_2, O_3, hydrocarbon haze (Arney et al. 2018), C_2H_6 (Domagal-Goldman et al. 2011) and the false positive indicators O_2-O_2, CO and CO_2 (Schwieterman et al. 2016), and O_2 and CH_4 for existing ground-based telescopes using high-resolution spectroscopy (Lovis et al. 2017). These observations will be extremely challenging, however, as JWST's capabiltiies are insensitive to the deep atmosphere and surface where a range of biosignatures are most readily observed. In the case of ground-based high-resolution spectroscopy, it will be difficult to observe potential false positive indicators like the broad absorption of O_2-O_2 in abiotic O_2 atmospheres. More thorough searches for biosignatures in the deep atmospheres of exoplanets and on their surfaces will be possible with large space-based direct imaging telescope concepts that are currently under development.

A NEW GENERATION OF MISSIONS

The increasing number of international partnership opportunities, as well as private-public partnerships (see Chapter 7) and innovative technologies (see Chapter 5) means NASA has the opportunity over the next 20 years to reconceive the scale, frequency, and risk level of missions and instruments to advance astrobiology.

- How can small spacecraft enable innovative, more frequent, astrobiologically relevant missions, and those that may be more accommodating of higher risk?
- How can standard small spacecraft buses, communication and navigation systems, Entry, Descent and Landing (EDL) systems, De-orbit, Descent, and Landing (DDL) systems, measurement techniques, and science instruments be developed to allow planetary missions to be more frequent and cost effective?
- How can instrument suites in which the failure of a single instrument would not be life threatening to a mission allow more comprehensive ways to search for life in other worlds?

- How could the development of onboard image processing systems, requiring orders-of-magnitude more computing power and memory allocation than available on current spaceflight systems, leverage on systems currently being developed by private industry?
- Could investments in the biomedicine, food security and defense be leveraged in the development of instruments for in situ life detection?

Small satellites were the first to be launched into Earth's orbit at the beginning of the space age, but satellites sizes increased dramatically immediately afterwards because the instruments, flight, power, and telecom systems required by more sophisticated missions were substantially larger. In the last few decades, the miniaturization of electronics, flight, and telecom systems has been enabling small satellites to accomplish increasingly more sophisticated missions. Indeed, NASA just launched the first deep space mission consisting of two small spacecraft (Mars Cube One), as secondary payload to the InSight Mars lander mission. Mars Cube One (MarCO) is a pathfinder mission that is testing new miniaturized communications and navigation technologies.

Small spacecraft technology, especially in the area of hardware miniaturization and software developments, is expected to develop rapidly during the next 20 years, with the rapid increase in the number of small spacecraft being developed and launched into Earth's orbit by public and private companies (Figure 6.8). This has the potential to have a positive impact on planetary science and particularly astrobiology missions by allowing the development of low-cost, opportunistic secondary missions. The miniaturization of space instruments allows secondary payloads that can be more innovative and cost effective, but may incorporate higher levels of risk than those used in traditional missions. For example small satellites will allow orbital transponders and receivers to be placed in orbit to relay data collected during the critical phase of the primary mission back to Earth (as done by MarCO), as illustrated in Figure 6.9, and will allow small satellites to probe the atmospheres of planets and moons. These small satellites will have direct impacts on atmospheric, climate, surface and subsurface studies of solar system bodies.

A small satellites mission for investigating Europa's subsurface ocean has been conceptualized as secondary payload to the Europa Clipper mission (Figure 6.10). Meanwhile, in the upcoming decades, SpaceX is expeditiously moving forward with ambitious Mars missions that could deploy fleets of small satellites as secondary missions, while Blue Origin has been developing concepts for lunar missions that could also carry small satellites. Advancements in machine learning software and hardware can be leveraged to continue the integration of miniaturization technologies in space missions. This will like have a direct impact on astrobiological missions as discussed in Chapter 5.

Required Development in Next 20 Years

The United States is a leader in the development of innovative space missions that enable scientific discoveries that inspire and engage the public around the world (e.g., NASEM 2017). It is essential that the development of these missions continue not only because of their scientific value, but also because they inspire and contribute to the education of new generations of scientists, engineers, and technologists. The following sections examine some small-scale activities that may have big payoffs in the coming decades.

Small Satellite Technologies

Knowledge of the atmospheric density and wind profiles as a function of altitude is critical to the planning of Entry, Descent, and Landing (EDL) of Mars missions requiring precise landing for the collection of optimum samples for astrobiology studies. This is important because the absence of traces of life at any one Mars landing site, for example, does not mean absence of any life on Mars, if the punctuated habitability of the planet is taken into account (e.g., Westall et al. 2015). Thus, multiple in situ and sample return missions are necessary to search for traces of life on Mars. Most of the potentially inhabited niches on Mars are on a scale too small to be readily observed from space (unless they are as large as Home Plate, i.e., approximately 90 meters across). This means that options to include relatively small scale missions be examined.

Satellite-to-satellite (crosslink) radio occultation at Mars (and other planetary bodies with atmospheres) could provide data for detailed studies of atmospheric dynamics and climate. Radio occultation measurements by three or more smallsats could provide dense global coverage in periods of a week or less, enabling greatly improved understanding of global atmospheric processes for many planetary bodies across the solar system (Ao 2017). At the giant planets and Titan, where traditional radio occultation to Earth is limited to dawn or dusk, crosslink radio occultation measurements could provide the first coverage of the diurnal cycle.

Permission Pending

FIGURE 6.8 Past and projected number of small satellites launched by public and private companies
SOURCE: SpaceWorks © 2017.

The maturation of radio occultation (RO) technology is necessary because current smallsat technologies such as the Iris transponder were developed for communication and do not produce the necessary phase observables for occultation science. This constrains the measurements to X-band (7-8 GHz), making unambiguous measurements from the near surface to the ionosphere difficult (e.g., Withers 2010). Moreover, systems developed for communication are much more complex and expensive than a dedicated radio occultation instrument, requiring more power, volume and mass allocations than a dedicated instrument. This makes current technologies unaffordable for use in fleets of smallsats. Hence, in order for cost effective smallsats capable of performing radio occultations to be possible, key strategic knowledge gaps that prevent them from being implemented need to be filled. This can be done efficiently by leveraging existing global positioning system (GPS) radio occultation instrument packages developed for smallsats. These instruments can be transformed into instrument packages for use in deep space, with the addition of a transmitter to provide a reference signal to replace the GPS signals used at Earth.

If future planetary missions are to be more-frequent and -cost-effective than they are currently, technology developments in the following areas are required:

- Standard small spacecraft buses,
- Communication and navigation systems,
- Entry, descent and landing (EDL) systems,
- De-orbit, descent, and danding (DDL) systems,
- Mmeasurement techniques, and

- Science instruments.

Such developments would reduce fabrication and qualification costs in comparison with those of current systems. Moreover, they would allow the development of instrument suites for multiple missions, making the failure of single instruments less of a risk to the overall program.

An example of astrobiologically relevant smallsat mission is the Europa Clipper Cubesat Mission, a conceptdevelope by JPL and the University of Michigan. According to this concept, during a close flyby of Europa, Clipper will eject a cubesat that will then orbit Europa at an altitude of about 1,500 km, 1 europan radius. The cubesat could conduct multi-frequency magnetic induction sounding over two 85.2 hour orbital periods. This would allow the determination of the salinity and depth of Europa's ocean, quantities not measured by the Europa Clipper. Once Clipper returns to the region, 15 days later during its long looping elliptical orbit of Jupiter, the cubesat will transmit all data to Clipper and complete its mission.

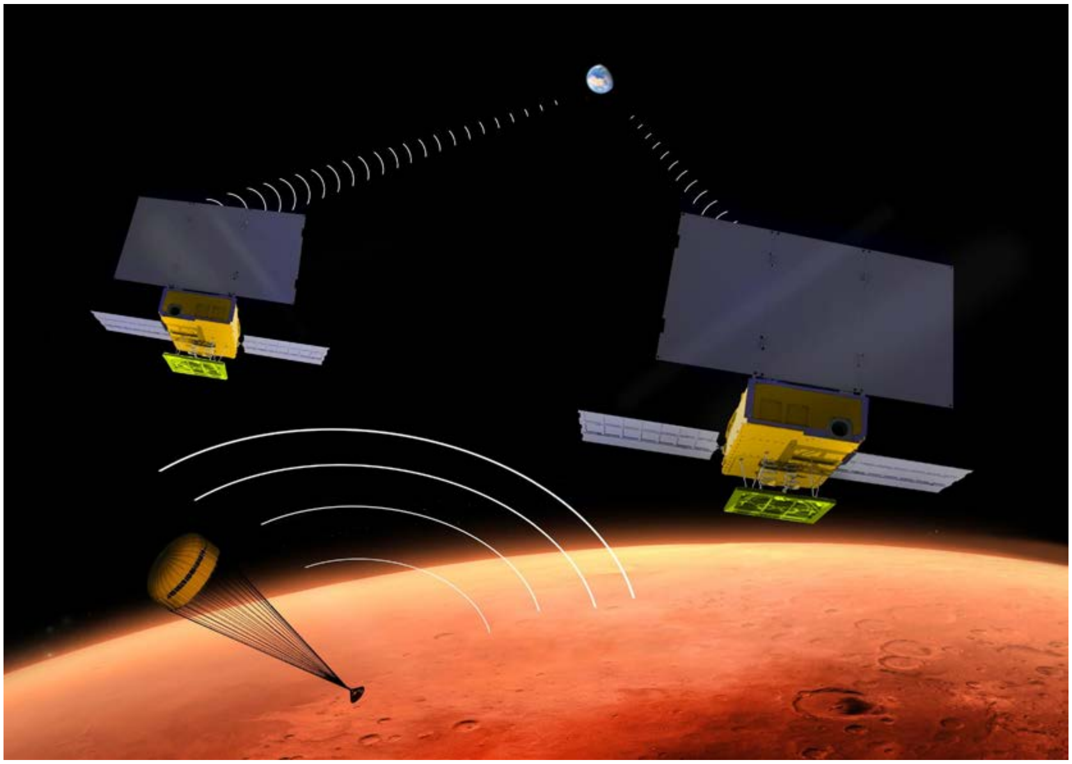

FIGURE 6.9 Artist rendition of Mars Cube One (MarCO) that are test-bed communication technologies for the twin CubeSat mission to Mars to aid in communications. SOURCE: NASA/JPL-Caltech.

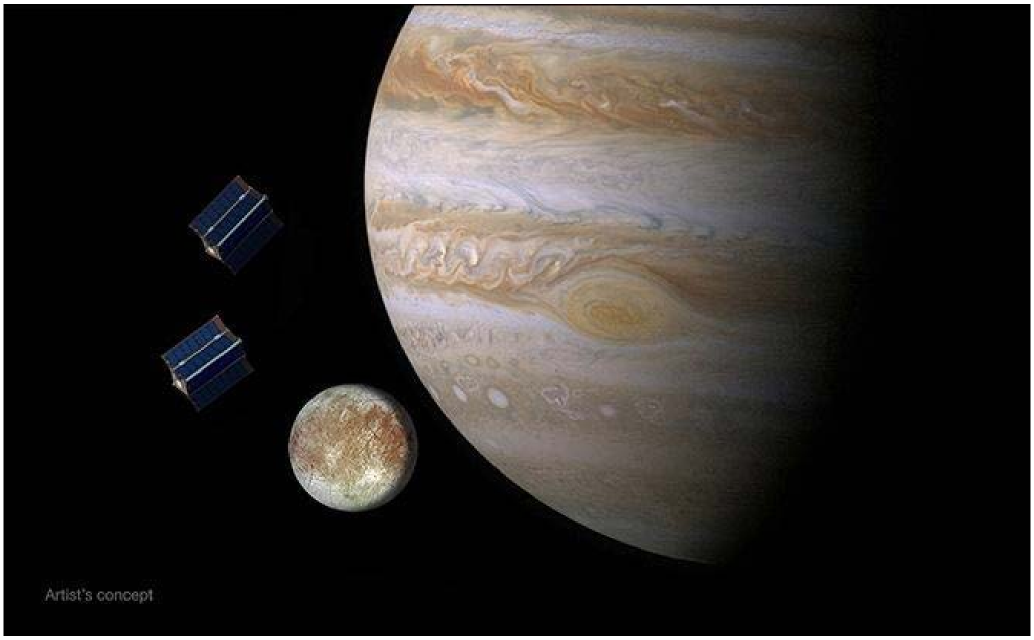

FIGURE 6.10 Artist rendition of CubeSats at Europa. These twin CubeSats are currently in a feasibility study to be included with the NASA Europa Clipper mission. SOURCE: NASA/JPL.

In Situ Life Detection

Investments in the biomedicine, food security, and defense sectors have led to large developments in instruments capable of in situ life detection. Comparably modest investments can will transform these commercial instruments into spaceflight hardware capable of addressing key astrobiology science goals, ensuring appropriate planetary protection requirements (Box 6.2) are met, and providing the computational and memory resources needed to support on-board data analysis. Relevant instruments that could be matured in the next two decades to accomplish astrobiological goals include, among others, miniaturized mass spectrometers, sample-compatible DNA sequencers, and optical microscopes. Analyses carried out onboard in support of these instruments may include searching images and other large data sets for features of interest using the exceptional computational capability developed by private industry and government in the past decades.

For example, onboard image processing – which could augment in situ sample analysis – demands orders-of-magnitude increases in computing power and memory allocation compared what is currently available for landed space missions. Furthermore, it is anticipated that onboard data analysis will become necessary because of the large constraints in data volume placed on surface missions to the ocean worlds, and possibly beyond. In these instances, increased resistance to and shielding from radiation may also be necessary.

Finally, the in situ search for life could also benefit from significant increases in bandwidth of the communication back to Earth. Because of this, moving forward optical communications with spacecraft in deep space will become increasingly necessary. In addition to data transfer, a larger communication bandwidth would allow onboard software to be updated more extensively and more frequently, as scientists and engineers on the ground analyze mission data and improve onboard processing techniques as they gain experience with mission operations.

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7

Leveraging Partnerships

As discussed in Chapter 5, the NASA Astrobiology program has excelled at implementing innovative programmatic elements that enhance communication and collaboration between communities engaged in astrobiological research. Creative partnering is not, however, new to NASA's Astrobiology program. From its earliest days, the NASA Astrobiology Institute (NAI) nucleated multi-disciplinary, multi-institutional teams of researchers funded under cooperative agreements with their lead institutions (Blumberg 2003). This arrangement, under which each NAI team's lead institution provided approximately 40% additional funding (Blumberg 2003), constituted a public-private partnership that successfully spurred independent investment in astrobiological research and magnified the impact of agency investments in the field.

Although programmatically innovative and diverse, the examples above demonstrate that NASA's Astrobiology Program has previously (and productively) focused on strengthening relationships with and between traditional academic communities. Building on this success, NASA is in a position to take advantage of more robust relations with the commercial sector as well. Increasingly related technological and methodological advancements made in the commercial sector and increasing interest in the field of astrobiology from philanthropic organizations and governments, both domestic and international, provide new opportunities to diversify the perspectives and resources brought to bear on the search for life in the universe.

POTENTIAL OF THE COMMERCIAL SECTOR

Chapter 5 highlights two areas in which leveraging not only the technology, but also the knowledge of the commercial sector, has a high potential to rapidly advance the search for life. Given the lack of business case in searching for life in the universe, however, the resources of the commercial sector can seem out of reach. The committee encountered two examples of non-traditional partnerships and collaborations that are successfully leveraging commercial sector technologies and capabilities and that have the potential to benefit the field of astrobiology or are actively doing so. Such examples serve as starting points from which the demonstrated collaborative creativity of the NASA Astrobiology program could explore future partnership opportunities.

The Frontier Development Lab

The innovative Frontier Development Lab (FDL), a research accelerator pioneered by the SETI Institute in partnership with NASA Ames Research Center (ARC), brings multiple leading technology companies, including Intel, NVIDIA, and Google, together with early career researchers in data science, astronomy, and planetary science to apply cutting edge artificial intelligence (AI) and machine learning (ML) methods to large, complex data sets (Cabrol et al. 2018). The partnership has grown out of a reciprocal need. On the one hand, researchers in astronomy and planetary science are being required to manage increasingly large and complex data sets, while on the other, companies invested in developing

AI and ML require large and complex datasets on which to test analyses and algorithms (Cabrol et al. 2018). Over the course of an intensive, eight-week workshop (see Table 7.1), FDL staff, mentors, and research teams of early-career scientists work together to identify problems that can be solved with novel AI and ML methods.

There is a high potential for success in applying the FDL partnership model to astrobiological research. The complexity, size, and multi-disciplinary nature of astrobiological datasets, which challenge conventional data analysis methods, make them ideal proving grounds for AI and ML technologies. Further, the FDL model itself is engineered to maximize the diversity of perspectives and resources used to solve scientific challenges. FDL staff and experts come from government (NASA ARC), research organizations (SETI Institute, USC Machine Learning Center), and multiple industries—from traditional aerospace (e.g., Lockheed Martin), to technology hardware and software (e.g., IBM, Intel, NVIDIA, and Google), to start-ups (e.g., X Prize) (Cabrol et al. 2018). Resources come not just in the form of capital (e.g., Space Resources Luxembourg), but also in donated hardware (NVIDIA), cloud computing (KX Systems, IBM, and Intel), and software services (e.g., Intel, IBM, and NVIDIA, to name only a few) (Cabrol et al. 2018). This wide variety of expert and early-career participants and diverse range of technologies and methods creates a space ideal for the innovation and creative problem-solving that is needed to advance the search for life.

TABLE 7.1 Frontier Development Lab 8-Week Project

Problem Phase	Week 1	Prototyping	Teams learn the problem domains and the skills of the FDL faculty
	Week 2	Big Ideas	Teams begin to work with their mentors to identify relevant data sets and novel analytical approaches to close knowledge gaps and pursue solution paths within their problem domain
	Week 3	Concept Definition	Teams are asked to close down on a concept for development, scope out its potential for breakthrough, and identify what specific tasks they will need to accomplish over the coming weeks to achieve their goals
Solution Phase	Week 4	Data Prep. and Prototyping	Teams begin conducting machine learning experiments to identify dead-end paths and most promising approaches
	Week 5	Prototyping and Pivoting	Mentors work with teams to develop their most promising approaches, adapt, and pivot if needed. Possibility of “talent trade” – where team members work on other projects
	Week 6	Prototyping and Demo	Teams produce and present a demo of their concepts and approaches. The first demo is internal with FDL staff and external advisors/coaches
Document Phase	Week 7	Document Draft	Preparation of formal 20 minute presentation, including solution demo and draft paper – presentation to senior NASA scientists and FDL staff
	Week 8	Presentations	Teams fine-tune “TED Talk” style presentation and demo of their work, and prepare final draft of a paper – presentation to review panel of NASA scientists and corporate/academic AI experts at FDL closing event

NOTE: The Frontier Development Lab is an intensive 8-week project bringing together industry experts, experienced researchers, and early career scientists to solve problems in planetary science and astronomy using artificial technology and machine learning methods.

SOURCE: After Cabrol et al. (2018), white paper submitted to the Committee on An Astrobiology Science Strategy for the Search for Life in the Universe, reproduced with the permission of Nathalie Cabrol and William H. Diamond, Jr., SETI Institute/FDL Summer Research Accelerator.

Connecting Scientists with Industry

While initiated as a partnership between NASA ARC and the SETI Institute, one of the greatest strengths of the FDL model is that it brings together government, academic, and industry participants to address a common goal. There is potential in such a partnership model not only to better connect industry opportunities with government science, but also to forge connections between individual researchers and industry partners, or even sponsors. As mission technologies become increasingly complex, the nascent technologies required to accomplish mission goals are increasingly likely to exist outside of the space sector. Concomitantly, flat or falling agency budgets necessitate leveraging investments that have already been made and diversifying funding sources, which can be substantially larger in the commercial sector (Carr 2018). Scientists acting between the commercial and public sectors may become pivotal in identifying opportunities to adapt and adopt commercial technologies for spaceflight. This path forward, however, poses both risks and challenges for research scientists (Carr 2018).

Identifying opportunities for collaboration with the commercial sector can depend heavily on personal connections and an alignment of interests not at the corporate, but at the personal, level. Personal connections between researchers and individuals with the ability to support research, or with influence over those can, is clearly advantageous. However, it does have its negative aspects. Researchers with good ideas, but lacking such connections, will be disadvantaged relative to those more senior or better connected. Funding decisions influenced by personal connections therefore raises important questions of equity, diversity and inclusiveness.

Collaborations with the commercial sector—particularly in a non-applied research field such as astrobiology—are unlikely to yield return on investment for the company, and thus tend to be an exchange of technology and ideas, with scientists finding alternative funding to support their work. Individual collaborations with the commercial sector may also be subject to market forces, founder decisions, and acquisitions or bankruptcy. If successful, however, such collaborations have the opportunity to both fund scientists and bring technology into the search for life that would otherwise be too expensive to re-engineer from the ground up. As the FDL partnership model shows, NASA could play a crucial role in providing networking opportunities for commercial entities and individual researchers, thereby laying the foundation for independent collaboration. Furthermore, the output from the agency sponsored or co-sponsored events would provide an immediate impact by diversifying the resource base supporting the search for life.

BOX 7.1
Technosignatures

Technosignatures are signs of technologically-advanced life, and are legitimate, if difficult to constrain, biosignatures for astrobiological searches. Examples include leakage from communication signals, or signals intentionally beamed to Earth. The search for technosignatures is a high risk, high reward approach to the search for life, and its probability of success is poorly understood. Although the search for extraterrestrial intelligence once received support from NASA, particularly in the development of specialized electronics for coupling to radio telescopes, federal support for project-level SETI efforts ended in 1993, and further NASA support has been episodic. Since 1993, private philanthropic endeavors have kept the search alive—allowing the creation of the Allen Telescope Array in Hat Creek, California, and piggyback searches on the giant Arecibo radio telescope in Puerto Rico.

Interest is once again growing in the search for technosignatures (Harp et al. 2016; Kuiper et al. 2016; Wright et al. 2016; Tellis and Marcy 2015; Maire et al. 2015). In 2015 the Breakthrough Foundation created Breakthrough Listen, a $100M USD pledge over ten years to fund the search for technosignatures with advanced radio and optical instrumentation. Thus far, Breakthrough Listen has been responsible for advancing the instrumentation and technosignature searches at the NRAO Green Bank Telescope (MacMahon et al. 2018; Enriquez et al. 2017) in West Virginia, USA, and the Murchison Widefield Array and Parkes telescope (Price et al. 2018) in Australia. Funds have also operated the Automated Planet Finder (APF) telescope at optical wavelengths at Lick Observatory, San Jose, CA to search for technosignature communication (Tellis and Marcy 2017). Breakthrough Listen is continuing to investigate investing in the next generation Meerkat telescope that is a pathfinder to the Square Kilometer Array optical searches using Cherenkov telescope (Abeysekara et al. 2016); data mining of existing optical and infrared astronomical data sets; and the design of dedicated optical and near-infrared observatories. Breakthrough Listen's directive is to conduct a search 50 times more sensitive than ever before that will cover 10 times more sky. This will benefit a swath of astrobiology and astronomical research fields.

In addition, there is increased international interest in technosignature research. Technosignature searches have been complemented with international facilities such as the Low Frequency Array in Europe and the Murchison Widefield Array in Australia (Tingay et al. 2018). In 2016, China finished the assembly of FAST (Five-hundred-meter Aperture Spherical radio Telescope), the world's largest radio dish at 500m (Nan et al. 2017), and through institutional collaborations has designed a new receiver specifically for the use of technosignature searches and research endeavors. Similarly, at optical wavelengths there have been international dedicated technosignature instruments developed in the last five years (Schuetz et al. 2016).

An important directive to technosignature researchers is to continue to operate at the forefront of technology and instrumentation to gain in sensitivity and search parameter space. New instrumentation has been able to lead directly to new astronomical discoveries and has directly benefited the access and quality of instrumentation for the broader community. For instance, recently improved radio receivers have directly led to the discovery and continuing characterization of a new class of objects, Fast Radio Bursts (Savchenko et al. 2018; Price et al. 2018; Gajjar et al. 2017). There is also increasing interest in making use of existing data with new analysis techniques for recognizing technosignatures (Griffith et al. 2015), as well as ensuring that new wide-field high cadence optical facilities like LSST and ZTF will be capable of identifying unusual transient events. Recent progress in the search for technologically advanced life forms has been coupled with the immense progress made in data analysis and signal detection in Big Data sets gathered by radio and optical wavelength telescopic monitoring of stars in the Milky Way galaxy.

Finding: International and philanthropic investment in the search for technosignatures over the last few years have greatly enhanced search capabilities. Corresponding improvements to radio and optical facilities have also benefited the broader scientific community.

FIGURE 7.1 Hubble Space Telescope image of Alpha Centauri A and B. The Alpha Centauri group is the closest star system to Earth and are primary target for the first direct imaging space telescopes, including the privately-funded Project Blue space telescope, searching for Earth-like planets. The distance between the two stars varies between 11 and 36 astronomical units over a period of approximately 80 years. Alpha Centaui C, also known as Proxima Centauri (not visible in this image), is some 13,000 astronomical units from A and B. SOURCE: https://www.nasa.gov/image-feature/goddard/2016/hubbles-best-image-of-alpha-centauri-a-and-b; courtesy of ESA and NASA.

INCREASING PHILANTHROPIC INVESTMENT

Much of the current diversity in resource base that exists in astrobiology originates from philanthropic investment. Examples of traditional philanthropic investment models include the Simons Foundation Collaboration on the Origins of Life, the Moore Foundation investment in the Thirty-Meter Telescope, the Kavli Foundation support for astrophysics, and the Heising-Simons Foundation awards in astronomy and cosmology. Additional, investment in the search for technosignatures (Box 7.1) has been sustained almost exclusively by the private sector for several decades. New investment models, however, are beginning to emerge, and the direction of astrobiological research in 2015 could not have anticipated the potential these models bring to the field. In late 2018, the Planetary Society's citizen-funded LightSail 2 spacecraft is anticipated to launch with the goal of accomplishing the first controlled, solar-powered flight in Earth orbit[1]. Although LightSail is not an astrobiological mission, its success as a crowd-sourced project illustrates a new level of public involvement and excitement in space science and new opportunities arising therefrom. The nonprofit BoldlyGo Institute[2] is currently capturing this same excitement to propel Project Blue—a direct imaging space telescope that will search the habitable zones of the nearest sunlike stars, Alpha Centauri A and B (Figure 7.1), in order to image Earth-like planets. Project Blue, which will advance the search for life in the universe, is funded both by a consortium of nonprofit institutes and organizations and by crowd sourcing. As the BoldyGo Institute indicates, recent

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[1] See http://www.planetary.org/explore/projects/lightsail-solar-sailing/.
[2] See http://www.boldlygo.org/.

private investments in astrobiological research are promoting a shift in a less conventional direction—toward higher risk, higher payoff missions focused on the search for life itself. These examples demonstrate how the search for life in the universe is able to channel imagination and excitement into partnerships that advance the necessary science and technology further and faster than can be done alone.

The committee was presented with one such example, Breakthrough Initiatives,[3] established out of the Breakthrough Prizes organization in 2015. Since its inception, this organization has invested millions of dollars in the search for life in the universe and has pledged to invest on the order of one hundred million over the coming years (Worden 2018). Although these funds are being allocated more slowly than initially anticipated, Breakthrough Initiatives has already made significant contributions to projects such as Automated Planet Finder at Lick Observatory and the MeerKAT radio telescope in South Africa.[4] The funds are being spread across a range of activities—from radio searches for extraterrestrial intelligence (Breakthrough Listen), to developing the technology for an interstellar probe (Breakthrough Starshot), to searching for potentially life-bearing exoplanets using biosignatures (Breakthrough Watch)—that at high cost have great potential for discovery. This potential is increased by Breakthrough's willingness to explore partnership ideas with NASA in high-risk/high-payoff activities, for instance, in a potential life-seeking mission to the ocean worlds (Worden 2018). With increasing philanthropic interest in astrobiological missions, future opportunities to pool technological, scientific, and funding resources using joint government-philanthropic life-seeking missions may be on the horizon.

MANAGING PUBLIC-PRIVATE PARTNERSHIPS

As recently highlighted in a study of public-private partnerships conducted by the Aerospace Corporation's Center for Space and Policy Strategy, the variety in types and goals of public-private partnerships "explains why [they] have no single, widely accepted recipe for success" (Jones 2018). During its discussion with experts in public-private partnerships, the committee identified two key questions that can help to create a successful partnership:

- Are you managing the private party's expectations? To ensure the private investment is sustained, it is vital to work closely with the private party to explain how the investment is used and what can reasonably be accomplished with their level of investment.
- Is the private party receiving their expected return on investment? In the example of the FDL partnership, the metric of success in this area is the willingness of investors and corporate partners to return each year with staff, donated technology resources, and financial support.
- Is the partnership capable of contributing to the science of astrobiology, providing innovative approaches to answering fundamental astrobiological questions, while allowing for mutual benefits to the personnel and infrastructure that NASA's astrobiology studies depend on?

Identifying opportunities with the potential to become fruitful partnerships, however, can be difficult. The committee met with representation from the Foundation for the National Institutes of Health (FNIH)—an independent, non-profit organization chartered by Congress to bring together corporations, research organizations, and private individuals to advance the mission of the NIH—to learn how mutually favorable opportunities can be identified and transformed into efficient partnerships. Because of potential conflict between a private sponsor's desires and agency science, a key factor of partnership success is absolute clarity of objectives and goals. This clarity is essential to finding areas of benefit for all partners as well as finding private endeavors into which NASA could most beneficially infuse support.

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[3] See https://breakthroughinitiatives.org/.

[4] For more information about the Automated Planet Finder and the MeerKAT radio telescope see https://www.ucolick.org/public/telescopes/apf.html and http://www.ska.ac.za/science-engineering/meerkat/, respectively.

Alternatively, or additionally, the agency could approach partnerships by identifying gaps in its own portfolio and seeking private funding or collaborations to address those gaps. Given the public interest in astrobiology, the search for life, and the search for life's origins on Earth, there may be potential for a similar arrangement in which a non-profit foundation could identify and manage private and/or commercial partnerships, raise funds, and administer research, educational, and training programs in astrobiology while ensuring that the mission of NASA's Astrobiology program is preserved and amplified.

The proliferation of opportunities for furthering astrobiological research from the commercial sector, increasing numbers of high-risk, high-payoff philanthropic investments in astrobiology, and new partnership models create an environment in which there is little reason for NASA's Astrobiology program not to participate. As such, it is important that NASA has the authorization to leverage any such venture that could dramatically advance the search for life in the universe. In return, the agency can:

- Take advantage of the private sector's ability to engage in high-risk, high-payoff activities;
- Leverage the ability of the private sector to act nimbly and efficiently to connect government to industry;
- Accomplish missions and achieve research goals that cannot be carried out with a single funding source; and,
- Enhance the diversity of the field's financial, technical, and human capital resource base.

Finding: The search for life beyond Earth presents attractive opportunities for public, private, and international partnerships.

UNIFIED INTERAGENCY INVESTMENT STRATEGIES

NASA's Astrobiology Program dedicates a wedge of funding each year to interagency partnerships intended to further the search for life in the universe (Voytek 2018). Coordination with the NSF, particularly, has led to new collaborations across disciplinary expertise often stove-piped by long-standing agency and disciplinary norms. For example, in 2016 NASA and NSF co-sponsored a Joint Ideas Lab that included both an intensive workshop and a funding solicitation that has continued to the present focused on the Origins of Life. The overarching goal of the Ideas Lab was to foster transformative, cross-cutting, and cross-disciplinary research approaches that integrate both the "metabolism first" and "genetics first" theories for the origins of life in order to inform the requirements for life on Earth as well as our search for life elsewhere. The joint agency workshop brought together disciplinary expertise from Earth science, planetary science, geochemistry, biochemistry, astrobiology and biology to address the origins of translation. The weeklong workshop included 29 participants selected from 130 applications. Workshop activities focused on building teams of participants from traditionally disparate disciplines in order to generate novel and innovative approaches to critical questions in prebiotic chemistry and life's origins. Following the workshop, 11 teams submitted proposals, and 5 were funded (2 through NSF and 3 through NASA). A subset of participants led by early career scientists also submitted and were awarded an NSF Research Coordination Network grant for the Exploration of Life's Origins. The example demonstrates how interagency initiatives that encourage unconventional collaborations and innovative approaches to astrobiology research can expand the astrobiology research community to include disciplinary scientists who previously may have been peripheral to the astrobiology community.

There are, however, several mutual investments made by these two agencies in which a greater clarity of goals and joint strategic investment portfolio may be of benefit. For example, recent discoveries have elevated the solar system's ocean worlds as viable targets for the search for life. The potential for life in these environments, and the formation and preservation of such life's biosignatures can be explored in the extreme habitats of Earth's deep oceans and polar regions. Furthermore, the ice shelves and deep oceans of our own planet are ideal test beds for technology development for future exploration of potentially habitable ocean and icy worlds. The success of such analog research depends critically on access to these environments. While some analog research is conducted through the NSF Office of Polar Programs or within the NSF Biological Sciences and Geosciences directorates, most of the research funding for this analog research comes through the NASA Astrobiology Program and affiliated R&A funding opportunities. In contrast, access to the polar regions as well as the United States fleet of scientific research vessels—operated by UNOLS (the University-National Oceanographic Laboratory System)—is within the purview of NSF. As NASA-funded research programs to these environments expand, better coordination between NASA and NSF to facilitate polar region and fleet access will be required.

In a similar vein, both the NSF and NASA support major ground-based observatories that play important roles in advancing astrobiology research. For example, the NSF supports the National Optical Astronomy Observatory (NOAO) observatories at Kitt Peak (Arizona) and on Mauna Kea (Hawaii) as well as the National Radio Astronomy Observatory (NRAO), which has radio wave telescopes in West Virginia and New Mexico. NASA funds the InfraRed Telescope Facility on Mauna Kea and is a minor partner with the private sector on the twin 10-m class Keck telescopes on Mauna Kea. NASA also supports the Large Binocular Telescope on Arizona’s Mount Graham, whose infrared interferometer is used to detect and measure the extent of exozodiacal dust around stars typical of those to be searched for habitable planets. A coordinated space- and ground-based strategy for detecting exoplanet biosignatures, informed by a systems science approach, would be useful to make the best use of both of these powerful avenues.

Recently, NSF and NASA acknowledged a shortage of high-precision radial velocity spectrometers capable of determining lower mass bounds for Earth-size exoplanets and available for follow-on observations in support of NASA missions such Kepler and TESS. In result, the two agencies have committed to funding a large portion of the observation time on the existing 3.5-m WIYN (Wisconsin-Yale-Indiana-NOAO) telescope on Kitt Peak. Further, they will support the design and construction of a new precision radial velocity spectrometer for use on the WIYN telescope in order to perform exoplanet follow-on observations.

While this agreement provides a good example of successful investment between NASA and NSF in advancing a unified ground- and space-based exoplanet strategy, further opportunities for collaboration exist. NSF has yet to invest significant resources in the giant segmented mirror telescope (GSMT) project that was prioritized as third of four large scale activities in the 2010 Astronomy and Astrophysics decadal survey (NRC 2010). The two U.S. GSMT projects (the Giant Magellan Telescope and the Thirty Meter Telescope) are anticipated to have high precision radial velocity spectrometers capable of determining the masses of transiting Earth-like exoplanets discovered by space telescopes. The addition of a coronagraph to either could allow direct imaging of the closest Earth-like planet, Proxima Centauri b, in the mid-2020s, well before any direct imaging mission recommended by the 2020 Astronomy and Astrophysics decadal survey could begin development. However, both projects are struggling with the billion-dollar costs of construction. NASA may be able to hasten progress in these projects by partnering with NSF in supporting at least one of the GSMTs, particularly if adaptive optics and a coronagraph are included to permit the detection and characterization of nearby Earth-like worlds.

> **Finding:** Space-based observation of nearby transiting Earth-like planets orbiting M-dwarf stars will be enhanced by complementary data sets acquired by ground-based giant segmented mirror telescopes—e.g., direct imaging, radial velocity measurements, and atmospheric spectra.

> **Finding:** Unified research strategies between relevant entities—including, but not limited to NASA, NSF, and NOAA—for conducting research in shared areas (e.g., polar regions and other difficult-to-access analog environments) and with shared infrastructure (e.g., ground- and space-based telescopes) would facilitate advances in astrobiology.

INTERNATIONAL OPPORTUNITIES

Since its earliest days, the Astrobiology Program through the NAI has pursued a progressive model for establishing international partnerships (Blumberg 2003). Potential partners can request association with the NAI at a government-to-government level (associate partners) or at the institute-to-organization level (affiliate partners). At the time of this writing, the NAI has two associate partners and 12 affiliate partners (see https://nai.nasa.gov/international-partners/). Both associate and affiliate international partnerships are conducted with no exchange of funds and consist primarily of collaborative scientific exchange and early career training opportunities (Blumberg 2003). In addition to bringing a diversity of perspectives and resources to the field, such associations have the potential to raise the profile of international astrobiology programs, increasing the chance of investment in associate or affiliate partners by their home governments, as occurred with the Spanish Astrobiology Center shortly after its association with the NAI was established (Blumberg 2003).

Although, like interagency missions, international space missions do not reduce total mission costs (NRC 2011a), they are able to reduce up-front expenditures and, most importantly, they unite nations in the pursuit of a common goal and bring a diversity of problem-solving capabilities to increasingly complex mission concepts. Perhaps nowhere is this more apparent than in the Joint Statement of Intent signed on April 26th, 2018 between NASA and ESA regarding Mars Sample Return (MSR). The statement emphasizes the common goal between NASA and ESA and sets a deadline of end-2019 for the agencies to have established their respective roles and responsibilities in the multi-mission Mars sample-return campaign (see Box 6.1). Unlike prior planned international collaborations that did not follow through for lack of funding or prioritization, the consensus of the U.S. (NRC 2011b) and European scientific communities on the value of an MSR campaign demonstrates a key requirement of success in successfully carrying out an international mission. Further, the rigorous planetary protection (see Box 6.2) discussion that will need to be had in the international arena concerning the return of martian samples to Earth, and possible research directions stemming from that discussion, will be of particular utility to the astrobiology community as it seeks to further understanding of the limits of known life and potential for extant life on Mars.

The goal of detecting and characterizing life on nearby exoplanets is such an immense challenge that it is not clear that any single space agency will be able to achieve this goal. NASA and ESA have a lengthy record of collaboration on major missions, such as the Hubble Space Telescope and JWST, which also includes contributions from the Canadian Space Agency. The committee discussed the idea, first suggested by European astronomers a decade ago in the context of joint NASA/ESA direct-imaging space telescopes, that NASA join with ESA and other like-minded agencies in seeking to found a new international organization dedicated to the goal of detecting and characterizing life on nearby exoplanets. Member nations would pledge to guarantee the sustained funding required to achieve this goal over a multi-decadal time scale. Such a steady funding steam would be the most efficient approach to supporting the development and construction of a direct-imaging space telescope capable of searching hundreds of nearby stars for possibly habitable exoEarths.

Several models for how such an international body might be structured, organized, and funded exist; relevant examples include the following:

- CERN,[5] the European Organization for Nuclear Research, with 22-member nations, unites the worldwide community of researchers in the field of elementary-particle physics by the provision of state-of-the-art accelerators and ancillary facilities;
- International Thermonuclear Experimental Reactor (ITER) Organization,[6] with 35 member nations, supports a worldwide effort to demonstrate that a sustained nuclear fusion can be achieved and become a feasible energy source for the future; and

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[5] For more information about CERN, see https://home.cern/.

[6] For more information about ITER, see https://www.iter.org/.

- European Southern Observatory (ESO),[7] with 16 member nations, exists to provide European astronomers with access to the some of the most capable astronomical telescopes from several of the best observing sites in the Southern Hemisphere.

Finding: The nucleation of government-level astrobiological partnerships that has been initiated by NASA has the potential to precipitate formation of an international organization with a unified focus on solving the immense challenges of detecting and confirming evidence for life within and beyond the solar system.

Recommendation: NASA should actively seek new mechanisms to reduce the barriers to collaboration with private and philanthropic entities, and with international space agencies to achieve its objective of searching for life in the universe.

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[7] For more about ESO, see https://www.eso.org/public/.

Appendixes

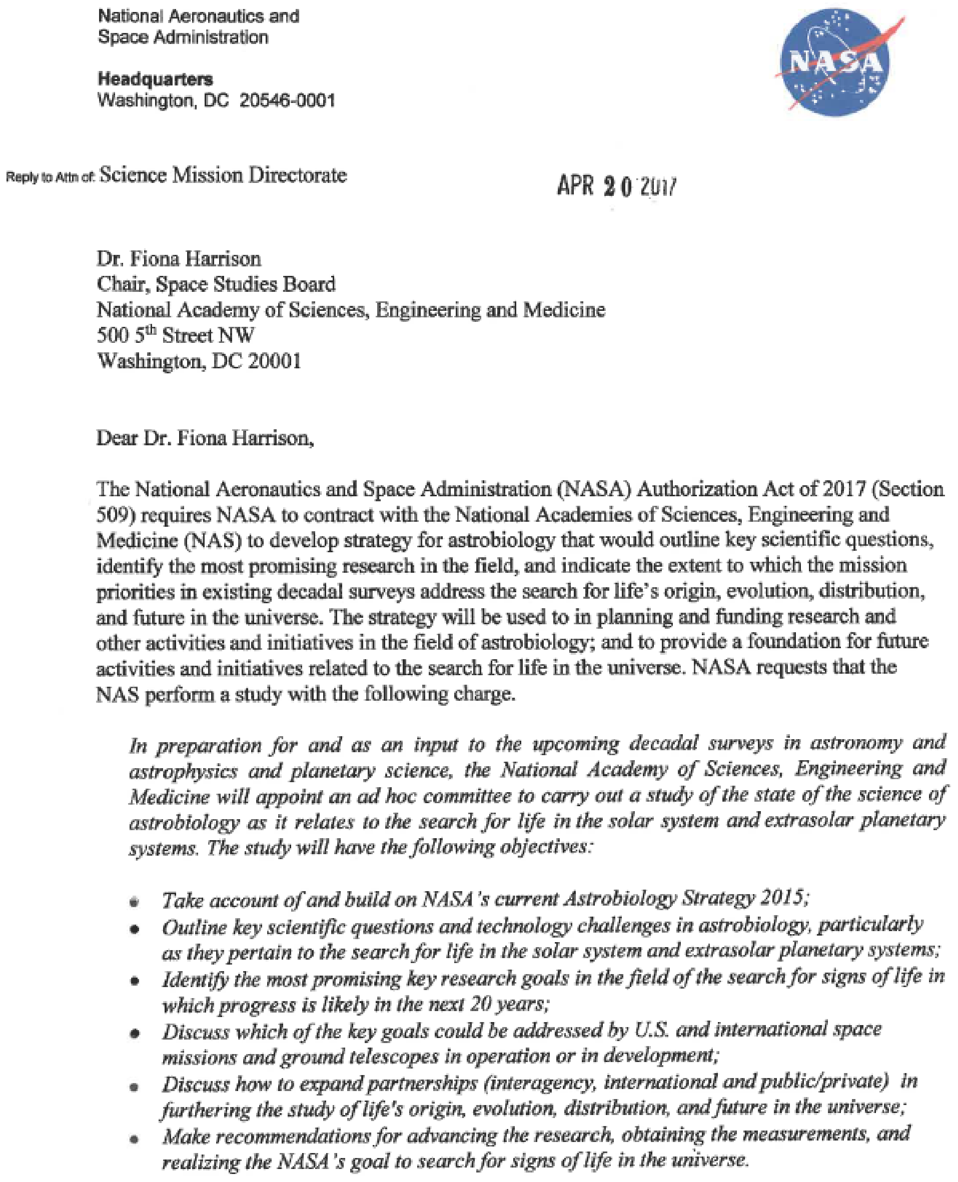
A

Congressional Mandate and Letter of Request

The mandate to carry out this study originated with the National Aeronautics and Space Administration (NASA) Transition Authorization Act of 2017, which stated:

> National Aeronautics and Space Administration Transition Authorization Act of 2017 (P.L. 115-10), Section 509
>
> SEC. 509. ASTROBIOLOGY STRATEGY.
>
> (a) STRATEGY.—
>
> (1) IN GENERAL.—The Administrator shall enter into an arrangement with the National Academies to develop a science strategy for astrobiology that would outline key scientific questions, identify the most promising research in the field, and indicate the extent to which the mission priorities in existing decadal surveys address the search for life's origin, evolution, distribution, and future in the Universe.
>
> (2) RECOMMENDATIONS.—The strategy shall include recommendations for coordination with international partners.
>
> (b) USE OF THE STRATEGY.—The Administrator shall use the strategy developed under subsection (a) in planning and funding research and other activities and initiatives in the field of Astrobiology.
>
> (c) REPORT TO CONGRESS.—Not later than 18 months after the date of enactment of this Act, the National Academies shall submit to the Administrator and to the appropriate committees of Congress a report containing the strategy developed under subsection (a).

In response to this congressional mandate, NASA's associate administrator for the Space Science Mission Directorate sent the following letter to the chair of the Space Studies Board:



National Aeronautics and
Space Administration

Headquarters
Washington, DC 20546-0001

Reply to Attn of: Science Mission Directorate

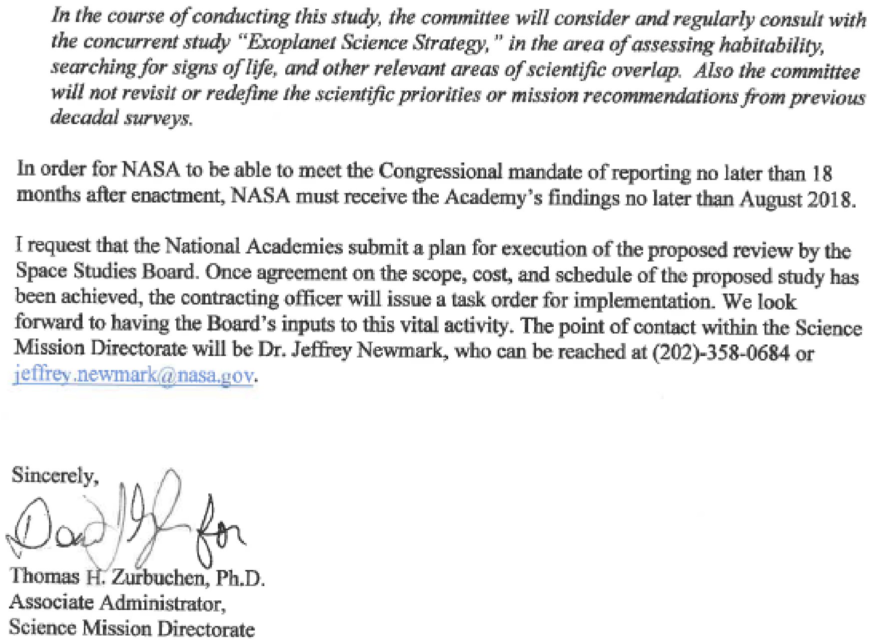
APR 20 2017

Dr. Fiona Harrison
Chair, Space Studies Board
National Academy of Sciences, Engineering and Medicine
500 5th Street NW
Washington, DC 20001

Dear Dr. Fiona Harrison,

The National Aeronautics and Space Administration (NASA) Authorization Act of 2017 (Section 509) requires NASA to contract with the National Academies of Sciences, Engineering and Medicine (NAS) to develop strategy for astrobiology that would outline key scientific questions, identify the most promising research in the field, and indicate the extent to which the mission priorities in existing decadal surveys address the search for life's origin, evolution, distribution, and future in the universe. The strategy will be used to in planning and funding research and other activities and initiatives in the field of astrobiology; and to provide a foundation for future activities and initiatives related to the search for life in the universe. NASA requests that the NAS perform a study with the following charge.

> *In preparation for and as an input to the upcoming decadal surveys in astronomy and astrophysics and planetary science, the National Academy of Sciences, Engineering and Medicine will appoint an ad hoc committee to carry out a study of the state of the science of astrobiology as it relates to the search for life in the solar system and extrasolar planetary systems. The study will have the following objectives:*
>
> - *Take account of and build on NASA's current Astrobiology Strategy 2015;*
> - *Outline key scientific questions and technology challenges in astrobiology, particularly as they pertain to the search for life in the solar system and extrasolar planetary systems;*
> - *Identify the most promising key research goals in the field of the search for signs of life in which progress is likely in the next 20 years;*
> - *Discuss which of the key goals could be addressed by U.S. and international space missions and ground telescopes in operation or in development;*
> - *Discuss how to expand partnerships (interagency, international and public/private) in furthering the study of life's origin, evolution, distribution, and future in the universe;*
> - *Make recommendations for advancing the research, obtaining the measurements, and realizing the NASA's goal to search for signs of life in the universe.*



> *In the course of conducting this study, the committee will consider and regularly consult with the concurrent study "Exoplanet Science Strategy," in the area of assessing habitability, searching for signs of life, and other relevant areas of scientific overlap. Also the committee will not revisit or redefine the scientific priorities or mission recommendations from previous decadal surveys.*

In order for NASA to be able to meet the Congressional mandate of reporting no later than 18 months after enactment, NASA must receive the Academy's findings no later than August 2018.

I request that the National Academies submit a plan for execution of the proposed review by the Space Studies Board. Once agreement on the scope, cost, and schedule of the proposed study has been achieved, the contracting officer will issue a task order for implementation. We look forward to having the Board's inputs to this vital activity. The point of contact within the Science Mission Directorate will be Dr. Jeffrey Newmark, who can be reached at (202)-358-0684 or jeffrey.newmark@nasa.gov.

Sincerely,

Thomas H. Zurbuchen, Ph.D.
Associate Administrator,
Science Mission Directorate

B

Statement of Task

In preparation for and as an input to the upcoming decadal surveys in astronomy and astrophysics and planetary science, the National Academies of Sciences, Engineering, and Medicine will appoint an ad hoc committee to carry out a study of the state of the science of astrobiology as it relates to the search for life in the solar system and extrasolar planetary systems.

The study will have the following objectives:

- Take account of and build on NASA's current Astrobiology Strategy 2015;
- Outline key scientific questions and technology challenges in astrobiology, particularly as they pertain to the search for life in the solar system and extrasolar planetary systems;
- Identify the most promising key research goals in the field of the search for signs of life in which progress is likely in the next 20 years;
- Discuss which of the key goals could be addressed by U.S. and international space missions and ground telescopes in operation or in development;
- Discuss how to expand partnerships (interagency, international and public/private) in furthering the study of life's origin, evolution, distribution, and future in the universe;
- Make recommendations for advancing the research, obtaining the measurements, and realizing NASA's goal to search for signs of life in the universe

In the course of conducting this study, the committee will consider and regularly consult with the concurrent study "Exoplanet Science Strategy," in the area of assessing habitability, searching for signs of life, and other relevant areas of scientific overlap. Also the committee will not revisit or redefine the scientific priorities or mission recommendations from previous decadal surveys.

C

List of White Papers

Input from the greater scientific community in the form of white papers has been an essential part of the decadal surveys process for many years. Such submissions help to ensure that the members of survey committee are exposed to as wide a diversity of ideas as is practicable. Given that the current study was designed to feed into the upcoming decadal surveys in astronomy and astrophysics and planetary science, the committee decided that it was important to give members of the astrobiology and related communities an opportunity to share their ideas and views concerning the most recent advances in the discipline and important avenues for future efforts.

A web-based submission mechanism was established several months prior to the committee's first meeting and white papers were accepted from November 7, 2017 through January 8, 2018. One expressed goal of the white-paper process was to promote broad community participation. For this reason, consensus-driven papers with many authors were particularly encouraged for submission. Specifically, members of the community were asked to submit white papers touching upon at least one of the following, pertaining to the search for life's origins, evolution, distribution and future in the universe:

- Significant scientific or technological progress since publication of the NASA Astrobiology Strategy 2015;
- Important scientific or technological topics omitted from the NASA Astrobiology Strategy 2015;
- Promising key research goals for which near-term progress is likely;
- Technological challenges in astrobiology;
- Key scientific questions in astrobiology;
- Scientific advances that can be addressed by U.S. and international space missions and relevant ground-based activities; and
- How to expand partnerships (interagency, international and public/private) to advance the goals of astrobiology

For the purposes of file management, in addition to meeting the January 8 deadline, authors were asked to limit their submissions to five single-spaced pages to receive full consideration. Additionally, all co-authors were required to give explicit permission prior to submission. Where appropriate several are cited in the main text of the committee's report. The authors and titles of the 52 white papers received can be found below and the full text of each can be found at http://sites.nationalacademies.org/SSB/CurrentProjects/SSB_180812.

1. Nadeau, J., C. Lindensmith, W. Fink, D. Schulze-Makuch, K.H. Nealson, L.M. Barge, H. Sun, J. Bowman, and I. Kanik. 2018. Just Look! White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.

2. Wright, J.T. 2018. SETI is Part of Astrobiology. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
3. Turyshev, S.G., M. Shao, and L. Friedman. 2018. A Mission to Find and Study Life on an Exoplanet: Using the Solar Gravity Lens to Obtain Direct Megapixel Imaging of a Putative Habitable World and High-Resolution Spectroscopy of its Atmosphere. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
4. Malaska, M.J., M.L. Cable, R. Hodyss, S.M. MacKenzie, J.I. Lunine, P.M. Beauchamp, C.R. Glein, M.L. Wong, C.A. Nixon, C.D. Neish, and M.G. Trainer. 2018. Seeking non-aqueous life on a hydrocarbon world. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
5. Chatterjee, S. 2018. Hydrothermal Impact Crater-Lakes and the Origin of Life. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
6. Cabrol, NA., Diamond, W.H., Altaf, N., Bishop, J., Cady, S.L, Fenton, L., Hinman, N., et al., 2018. Advancing Astrobiology Through Public/Private Partnerships: The FDL Model. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
7. Snyder, D.P. 2018. A Better Biologically Informed Manned Mission to Mars. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
8. Davila, A., C.P. McKay, D. Willson, J. Eigenbrode, and T. Hurford. 2018. Follow the plume: Organic molecules and habitable conditions in the subsurface ocean of Enceladus. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
9. Vance, S.D., S. Kedar, M.P. Panning, S.C. Stahler, and R.D. Lorenz. 2018. Geophysical Investigations of Habitability in Icy Ocean Worlds. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
10. Haqq-Misra, J., S. Som, B. Mullan, R. Loureiro, E. Schwieterman, L. Seyler, H. Mogosanu, et al. 2018. The Astrobiology of the Anthropocene. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
11. Van Kranendonk, M.J., R. Baumgartner, E. Boyd, S. Cady, K. Campbell, A. Czaja, B. Damer, et al. 2018. Terrestrial Hot Springs and the Origin of Life: Implications for the Search for Life Beyond Earth. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
12. Hendrix, A.R., T. Hurford, J. Amend, M. Aye, M. Bannister, L. Barge, P. Beauchamp, et al. 2018. Roadmaps to Ocean Worlds (ROW): Goals, Objectives, Investigations. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
13. Hendrix, A.R., T. Hurford, J. Amend, M. Aye, M. Bannister, L. Barge, P. Beauchamp, et al. 2018. Roadmaps to Ocean Worlds (ROW): Priorities. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
14. Cabrol, N.A., J. Bishop, S.L. Cady, N. Hinman, J. Moersch, N. Noffke, C. Phillips, P. Sobron, D. Summers, and D. Wettergreen. 2018. Bridging Strategic Knowledge Gaps in the Search for Biosignatures on Mars. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.

15. Cable, M.L., C.D. Neish, M.J. Malaska, S. MacKenzie, C.A. Nixon, R. Hodyss, A. Hayes, et al. 2018. Seeking the origins of aqueous life on Titan. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
16. Hand, K.P., A.E. Murray, J.B. Garvin, W.B. Brinckerhoff, B. Christner, K.E. Edgett, B. Ehlmann, et al. 2018. Astrobiological Potential of the Europa Lander Mission Concept. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
17. Cabrol, N.A., L.K. Fenton, W.H. Diamond, N. Hinman, G. Mackintosh, J. Moersch, P. Sobron, K. Warren-Rhodes, D.S. Wettergreen, and K. Zacny. 2018. Mission Concept – High-Resolution Mars Environmental Sensor Array. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
18. Giri, C., T. Jia, H.J. Cleaves II, T. Usui, D. Bodas, C. Carr, H. Chen, et al. 2018. Life-Detection Technologies for the Next Two Decades. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
19. Fairén, A.G., D. Schulze-Makuch, V. Parro, L. Whyte, J. Bishop, J. Gómez-Elvira, C. Cockell, and A. Pavlov. 2018. Planetary Protection should enable the exploration of Mars and not prohibit it. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
20. Rummel, J.D., M.S. Race, and J.A. Spry. 2018. Planetary Protection: A Cross-Cutting Concern, and a Necessity for Basic and Exploration Driven Research in Astrobiology. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
21. Desch, S.J., S. Kane, C.M. Lisse, C.T. Unterborn, H.E. Hartnett, and S.-H. Shim. 2018. A procedure for observing rocky exoplanets to maximize the likelihood that atmospheric oxygen will be a biosignature. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
22. Cable, M.L., J.I. Lunine, J.H. Waite, C.R. Glein, C. Porco, L.J. Spilker, J.Baross, et al. 2018. Enceladus: A Review of Recent Discoveries. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
23. Laine, P.E. 2018. Habitability and Biosignatures. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
24. Clark, K.B. 2018. Searching for (Proto)Cellular Logics Proteins in Earth-like Environments Hospitable and Inhospitable to Life. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
25. Del Genio, A., V. Airapetian, D. Apai, N. Batalha, D. Brain, W. Danchi, D. Gelino, S. Domagal-Goldman, J.J. Fortney, W. Henning, and A. Rushby. 2018. Life Beyond the Solar System: Observation and Modeling of Exoplanet Environments. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
26. Williams, R.M.E., L.C. Kah, E.S. Boyd, D.E. Eby, M.V. Berg, T.C. Chidsey, D.R. Lageson, et al. 2018. The importance of formative conditions & biosignature characteristics in martian sample selection. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
27. Trainer, M.G., G.N. Arney, M.L. Cable, J.I. Lunine, S.J. Horst, C.A. Nixon, S.D. Domagal-Goldman, et al. 2018. “Pale Orange Dot”: Titan as an Analogy for Early Earth and Hazy Exoplanets. White

paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.

28. Craft, K., C. Bradburne, and C. Hibbitts. 2018. Life Detection Strategy and the Need for Robust Sample Preparation Techniques. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
29. Batalha, N.M., W. Danchi, E.B. Ford, J.J. Fortney, D. Huber, H. Jang-Condell, N. Turner, et al. 2018. Life Beyond the Solar System: Exoplanet Properties as Context for Planetary Habitability. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
30. Blank, J.G., T.L. Roush, C.L. Stoker, A. Colaprete, S. Datta, U. Wong, M. Deans, et al. 2018. Planetary Case as Astrobiology Targets. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
31. Clark, R.N., M. Gudipati, K.P. Hand, and K. Hibbitts. 2018. The Role of Laboratory Data to Interpret Results from Europa clipper: Mission Success, Habitability and Landing Site Characterization. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
32. Willis, P., W. Brinckerhoff, A. Ricco, J. Creamer, M.F. Mora, A. Noell, J. Eigenbrode, et al. 2018. A universal approach in the search for life at the molecular level. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
33. Hand, K.P., and C.B. Phillips. 2018. On the Past, Present, and Future Role of Biology in NASA’s Exploration of our Solar System. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
34. Taylor, S.F. 2018. Unexpected features in the distribution of counts of giant planets could have an influence the numbers of potentially habitable planets. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
35. Eigenbrode, J.L., B. Glass, C. McKay, P. Niles, and J. Spry. 2018. Martian subsurface ice science investigation with a special regions drill. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
36. Airapetian, V.S., W.C. Danchi, C.F. Dong, S. Rugheimer, M. Mlynczak, K.B. Stevenson, W.G. Henning, et al. 2018. Life Beyond the Solar System: Space Weather and Its Impact on Habitable Worlds. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
37. Ricco, A.J., M.B. Wilhelm, R.C. Quinn, A. Davila, and D.J. Harrison. 2018. The Critical Role of Integrated Microfluidic Systems in the Search for Life: Key Challenges, Recent Progress, Path Forward. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
38. Pappalardo, R., C. Phillips, O. Abramov, N. Altobelli, A. Barrr, M.J. Blacksberg, S. Bolton, et al. 2018. Addressing the Habitability of Europa with the Europa Clipper Mission. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
39. Schwieterman, E., C. Reinhard, S. Olson, and T. Lyons. 2018. The Importance of UV Capabilities for Identifying Inhabited Exoplanets with Next Generation Space Telescopes. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.

40. Domagal-Goldman, S., N.Y. Kiang, N. Parenteau, D.C. Catling, S. DasSarma, Y. Fujii, C.E. Harman, et al. 2018. Life Beyond the Solar System: Remotely Detectable Biosignatures. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
41. Barnes, R., A. Shahar, C. Unterborn, H. Hartnett, A. Anbar, B. Foley, P. Driscoll, et al. 2018. Geoscience and the Search for Life Beyond the Solar System. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
42. Kane, S.R., G. Arney, D. Crisp, S. Domagal-Goldman, L.S. Glaze, C. Goldblatt, A. Lenardice, C. Unterborn, and M.J. Way. 2018. Venus: the Making of an Uninhabitable World. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
43. Johnson, S.S., H. Graham, E. Anslyn, P. Conrad, L. Cronin, A. Ellington, J. Elsila, et al. 2018. Agnostic Biosignatures: Towards a More Inclusive Life Detection Strategy. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
44. Tarter, J., J. Rummel, A. Siemion, R. Martin, C. Maccone, and G. Hellbourg. 2018. Three Versions of the Third Law: Technosignatures and Astrobiology. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
45. Hipkin, V. 2018. Canadian Science Priorities for Astrobiology. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
46. Siegler, N., M. Bolcar, B. Crill, S. Domagal-Goldman, E. Mamajek, and K. Stapelfeldt. 2018. Life Beyond the Solar System: Technology Needs. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
47. Ansdell, M., and P. Kalas. 2018. Expanding Public-Private Partnerships for NASA Astrobiology. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
48. Kuhn, J.R., S.V. Berdyugina, D. Apai, A.V. Berdyugin, D.C. Catling, T. Darnell, B. Diamond, et al. 2018. Exo-Life Finder (ELF): A Hybrid Optical Telescpe for Imaging Exo-Earths. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
49. Ehlmann, B., E. Kite, D. Rogers, T. Glotch, C. Fassett, A. Hayes, C. Edwards, et al. 2018. Mars as a Linchpin for the Understanding the Habitability of Terrestrial Planets: Discoveries of the Last Decade from Mars and Why a New Paradigm of Multiple, Landed Robotic Explorers is Required for Future Progress in Terrestrial Planet Astrobiology. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
50. Vlada, S., J. Barross, D. Beaty, B. Luther, M.S. Bell, J.G. Blank, D. Breuer, et al. 2018. Mars Subsurface Access: From Sounding to Drilling. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
51. Nguyen, M., and N. Tacconi. 2018. From Nucleotides to a LUCA. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.
52. Willson, D., R. Bonaccorsi, and C.P. McKay. 2018. Sample Collection and Contamination management for Life Detection in Ocean Worlds during Plume Fly-throughs. White paper submitted to the Committee on an Astrobiology Science Strategy for the Search for Life in the Universe, National Research Council, Washington, D.C.

D

Biographies of Committee Members

BARBARA SHERWOOD LOLLAR, C.C. FRSC, *Chair*, is a university professor at the University of Toronto in the Department of Geology. She is also director of the Stable Isotope Laboratory and Canada Research Chair in Isotopes of the Earth and Environment. She leads research programs in deep crustal fluids, hydrocarbon geochemistry, the deep subsurface biosphere, and groundwater quality and remediation. Her work in geochemistry and microbiology have led her to research the habitability of the isolated, deep hydrosphere and its implications for life elsewhere in the solar system. Dr. Sherwood Lollar is a Companion to the Order of Canada and a former president of the Geochemical Society. She has received the NSERC John C. Polanyi Award, the Eni Prize for the Protection of the Environment, and the GSA Geomicrobiology and Geobiology Division Award. Dr. Sherwood Lollar received her Ph.D. in Earth sciences from the University of Waterloo. She has served as a member of the Academies' Space Studies Board, a member of the Future of U.S. Civil Space Policy: A Workshop, the Committee on Astrobiology and Planetary Science, and the Committee on the Origins and Evolution of Life.

SUSHIL K. ATREYA is a professor of climate and space sciences and engineering at the University of Michigan. He is also director of the Planetary Science Laboratory at the University of Michigan. His research focus is the origin and evolution of planetary and satellite atmospheres (including giant planets, Titan, Mars, and Venus), planetary habitability, and exoplanets. He has served as a co-investigator on many planetary exploration missions including NASA's Mars Science Laboratory, Juno Jupiter Polar Orbiter, ESA's Mars Express, Cassini-Huygens, Galileo, Voyager, Venus Express, and a number of Roscosmos and JAXA missions. He has received the David Bates Medal of the European Geosciences Union for exceptional contributions to planetary and solar system sciences, the NASA award for exceptional scientific contributions to the Voyager missions to the giant planets, the NASA Group Achievement Awards for outstanding scientific contributions with the Voyager Ultraviolet Spectrometer, for exceptional technical innovations in surface operations of MSL Prime Mission, for outstanding scientific contributions with the Galileo Probe mass spectrometer, and for outstanding contributions to the Galileo Project at Jupiter. Dr. Atreya is a fellow of the American Association for the Advancement of Science, a member of the International Academy of Astronautics, and a distinguished visiting scientist at the Jet Propulsion Laboratory. He is the author of *Atmospheres and Ionospheres of the Outer Planets and their Satellites* as well as editor of *Origin and Evolution of Planetary and Satellite Atmospheres* and two other books. He has served as a co-chair of the Venus Exploration Analysis Group (VEXAG) and as a member of the Steering Committee of the Outer Planets Assessment Group (OPAG). He earned his B.S. and M.S. in physics from the University of Rajasthan, an M.S. in physics from Yale, and his Ph.D. in atmospheric and space science from the University of Michigan. Dr. Atreya has served as a member on the Academies' Committee on the Assessment of Solar System Exploration, the Panel on Space Sciences, and the Committee on Astrobiology and Planetary Science.

ALAN P. BOSS is a research staff member at the Carnegie Institution. Dr. Boss's research addresses the formation of stars and planetary systems by using both theoretical models of solar system formation and observational instruments and techniques. He helped develop the disk instability model of solar system formation. Dr. Boss is a member of the American Academy of Arts and Sciences, and is a fellow of the

American Association for the Advancement of Science, the Meteoritical Society, and the American Geophysical Union. He chairs NASA's Exoplanet Exploration Program Technology Assessment Committee and NASA's Exoplanet Exploration Program Analysis Group. He is also a member of NASA's Astrophysics Advisory Committee. Dr. Boss earned his Ph.D. in physics from the University of California at Santa Barbara. He has served on the Academies' Astro2010 Panel on Electromagnetic Observations from Space, the Committee on Planetary and Lunar Exploration, and the Committee for US-USSR Workshop on Planetary Sciences.

PAUL G. FALKOWSKI, NAS, is the Bennett L. Smith Professor of Business and Natural Resources at Rutgers, the State University of New Jersey. He is also director of the Rutgers Energy Institute. His research interests focus on three areas including the origin of life, electron transfer mediation, and how organisms transformed terrestrial geochemistry. In pursuing these interests, he is involved with research into biogeochemical cycles, biological oceanography, molecular biology, physiological adaptation, and plant physiology. He is also the lead principal investigator in the Environmental Biophysics and Molecular Ecology Program, which focuses on molecular biology and biophysics to address key questions in biological oceanography and marine biology. Dr. Falkowski's awards include the Rutgers University Board of Trustees Award for Excellence in Research and the European Geosciences Union's Vernadsky Medal. He earned his Ph.D. in biology from the University of British Columbia. Dr. Falkowski has served on many National Academies' committees, including the Committee on Environmental Science and Assessment for Ocean Energy Management, the Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts, and the 2015 NAS Class VI Membership Committee. He has served as chair of Section 63: Environmental Sciences and Ecology in the NAS.

JACK D. FARMER is a professor of geological sciences at Arizona State University in the School of Earth and Space Exploration. His research interests include microbial bio-sedimentology and the evolution of Earth's early biosphere. He is particularly interested in understanding the factors that control biosignature preservation and how that knowledge can be translated into strategies for the search for evidence of past life on Mars. Prior to joining the faculty at Arizona State University, Dr. Farmer was a research scientist in the Exobiology Branch of NASA's Ames Research Center. He was instrumental in the selection of the landing sites for Mars Pathfinder and the Mars Exploration Rovers. Dr. Farmer served on the science definition team for the Mars Odyssey and Mars Reconnaissance Orbiter missions. He has chaired the NASA Astrobiology Institute's Mars Focus Group and the community-based Mars Exploration Program Analysis Group. Dr. Farmer is a Sequoyah Fellow of the American Indian Science and Engineering Society. Dr. Farmer is a past member of NASA's Space Sciences Advisory Committee. He earned his Ph.D. in geology and paleobiology from the University of California, Davis. He has served on several Academies' boards and committees including the Space Studies Board, the Committee to Review the NASA Astrobiology Institute, the Committee for the Review of NASA Science Mission Directorate Science Plan, and the Committee on the Review of Planetary Protection Requirements for Mars Sample-Return Missions, which he chaired.

OLIVIER GUYON is an associate astronomer and associate professor of optical sciences at The University of Arizona in the Department of Astronomy and Steward Observatory. There, his research focuses on innovative techniques for detecting and imaging extrasolar planets, coronography, and wavefront sensing techniques for adaptive optics. He is also an affiliate of the Astrobiology Center of the National Institutes of Natural Sciences of Japan and of NASA's Jet Propulsion Laboratory. He serves as a member of NASA's science and technology definition teams for the WFIRST, HabEx, and LUVOIR mission concepts. Previously, Dr. Guyon worked as a project scientist with the Subaru Telescope of the University of Hawaii. He has been the recipient of the MacArthur fellowship, of the Presidential Early Career Award for Scientists and Engineers, and of the Daniel Guinier young researcher award of the

French Society of Physics. Dr. Guyon earned his Ph.D. in astronomy from the Pierre and Marie Curie University.

GERALD F. JOYCE, NAS/NAM, is a professor at the Salk Institute for Biological Studies. He is also institute director of the Genomics Institute of the Novartis Research Foundation (GNF). Broadly, Dr. Joyce's research concerns the origin of life itself. He is a pioneer in the field of in vitro evolution, which re-creates the biomolecules of early life, their assembly into RNA, and their evolution, all within the laboratory environment. His work has furthered the understanding of how life arose from abiotic chemistry. For this work, he has received the U.S. National Academy of Sciences Award in Molecular Biology and the U.S. National Academy of Sciences Miller Award. Dr. Joyce received his Ph.D. in neurosciences and chemistry and his M.D. in medicine from the University of California, San Diego. He previously served on the Academies' Committee on International Security and Arms Control and the 2004 NAS Award in Molecular Biology Selection Committee.

JAMES F. KASTING, NAS, is the Evan Pugh Professor at The Pennsylvania State University in the Department of Geosciences. His research interests include atmospheric evolution, planetary atmospheres, paleoclimates, and the search for habitable planets beyond the solar system. Previously, Dr. Kasting worked at the National Center for Amotpheric Research in Boulder, Colorado and the Space Science Division at NASA-Ames Research Center. He is a fellow of the American Association for the Advancement of Science, the International Society for the Study of the Origin of Life, and the American Geophysical Union. He has published dozens of papers and three books. Dr. Kasting earned his Ph.D. in atmospheric sciences from the University of Michigan. He has served on several Academies' committees, including the Committee on Astrobiology and Planetary Sciences, Searching for Life Across Space and Time: A Workshop, and the Committee on the Astrophysical Context of Life.

VICTORIA S. MEADOWS is a professor of astronomy at the University of Washington in the Department of Astronomy. There, she is also director of the Astrobiology Program and principal investigator for the NASA Astrobiology Institute's Virtual Planetary Laboratory. Her research interests include theoretical modeling of terrestrial planetary environments to understand their habitability, the generation and detectability of planetary biosignatures and their false positives, and solar system planetary observations. The overarching goal of her research is to determine how to recognize whether a distant extrasolar planet can or does support life. Previously, Dr. Meadows was a research scientist at the Jet Propulsion Laboratory and an associate research scientist at the Spitzer Science Center at the California Institute of Technology. She is a recipient of several NASA Group Achievement Awards, has been on the SETI Institute Science Advisory Board, and was a Frontiers of Science Kavli Fellow. She earned her Ph.D. in physics from the University of Sydney. Dr. Meadows served on the Academies' Searching for Life Across Space and Time: A Workshop committee.

PHILIP M. NECHES, NAE, is the founder of Teradata Corporation. He is a trustee of the California Institute of Technology and is a lead mentor and venture partner at Entrepreneurs Roundtable Accelerator in New York City. Dr. Neches's interests include big data, information systems architecture, nanotechnology, start-ups, business strategy, and engineering education. He has been an independent consultant, director, and advisor at a number of public and private information technology companies. Previously, he was vice president and group technology officer for the AT&T Multimedia Products and Services Group and senior vice president and chief scientist of NCR Corporation. Dr. Neches has received a Product of the Year Award on behalf of the Teradata Corporation. Dr. Neches received his Ph.D. in computer science at the California Institute of Technology. He has served on several Academies' committees including Searching for Life Across Space and Time: A Workshop, the Committee on A Vision for the Future of Center-Based, Multidisciplinary Engineering Research, and the Panel on Review of the Information Technology Laboratory at the National Institute of Standards and Technology.

CARL B. PILCHER is a research scientist at the Blue Marble Space Institute of Science. Previously, he acted as interim director of the NASA Astrobiology Institute (NAI), a position he accepted after retiring as director of the NAI. During his tenure he facilitated numerous multi-disciplinary collaborations, particularly within the Origins of Life research portfolio, and steered the institute toward a more direct, supportive role in spaceflight missions. Before moving to management of the NAI, Dr. Pilcher served as program scientist for NASA's Kepler Mission and NASA's participation in the Keck Observatory. His academic background includes a faculty position in the Department of Physics and Astronomy at the University of Hawaii, where he analyzed Neptune's atmosphere and participated in the discovery of methane ice on Pluto. As a graduate student, he led scientific teams that discovered water ice in Saturn's rings and on three of Jupiter's Galilean satellites including Europa. Dr. Pilcher has received the NASA Exceptional Achievement Medal, numerous Group Achievement Awards, and an Ames Honor Award. He received his Ph.D. in chemistry from the Massachusetts Institute of Technology. He has not previously served on an Academies' committee.

NILTON O. RENNÓ is a professor at the University of Michigan. He is also chair of the department's master's programs, and director of the Master of Engineering program in Space Engineering. Dr. Rennó's research interests include aerosols and climate, astrobiology, aviation, instrument development, planetary science, thermodynamics, and systems engineering. He studies the physical processes that control the climate of Earth and other planets and works on the design and fabrication of instruments for this purpose. Previously, Dr. Rennó was a tenured associate professor in the Department of Planetary Sciences at the University of Arizona. He has received the Space Foundation John L. "Jack" Swigert Jr. Award for Space Exploration, the American Institute of Aeronautics and Astronautics Foundation's Award for Excellence, and the National Aeronautic Association's Robert J. Collier Trophy for his work on NASA's Mars Science Laboratory and Curiosity rover missions, as well as several individual and NASA Group Achievement Awards. He earned his Ph.D. in atmospheric sciences from the Massachusetts Institute of Technology. He has served as a member on the Academies' Panel on Earth Sciences, Committee on the Review of MEPAG Report on Planetary Protection for Mars Special Regions, and Searching for Life Across Space and Time: A Workshop.

KARYN L. ROGERS is an assistant professor at Rensselaer Polytechnic Institute in the department of Earth and Environmental Sciences. There, Dr. Rogers' research focuses on the relationships between microbial communities and environmental conditions in extreme ecosystems and is broadly applied to understanding the nature and the origin of life on Earth, the potential for life throughout the solar system, and the extent of life in modern extreme environments. To study these themes and develop a holistic understanding of functional microbial ecosystems, she employs a combination of fieldwork in several terrestrial hydrothermal systems and modern deep-sea mid-ocean ridge environments with extensive laboratory analytical and experimental techniques. Previously, Dr. Rogers worked as a research scientist at the Carnegie Institution of Washington (now Carnegie Institution for Science), as an assistant professor at the University of Missouri, and as a postdoctoral scholar in the Deep Ocean Exploration Institute at Woods Hole Oceanographic Institution. She is associate director of the New York Center for Astrobiology, a member of the Institute for Data Exploration and Applications, and U.S. lead and co-director for the Sloan Foundation Deep Carbon Observatory's PRIME (Peizophile Retrieval Instrumentation for Microbial Explorations) Facility. She serves as co-organizer of the University-National Oceanographic Laboratory System Deep Submergence Science Committee New User Program. Dr. Rogers earned a Ph.D. in Earth and planetary sciences from Washington University, an A.M. in Earth and planetary sciences from Washington University, an M.S. in geological and environmental sciences from Stanford University, and an A.B. in environmental science and public policy and Earth and planetary sciences from Harvard University. She has not previously served on an Academies committee.

BRITNEY E. SCHMIDT is an assistant professor at the Georgia Institute of Technology. Dr. Schmidt is the principal investigator of the Ross Ice Shelf and Europa Underwater Probe (RISE-UP), an interdisciplinary astrobiology and oceanographic investigation leveraging remote sensing and autonomous underwater vehicles to examine Earth's ice shelves as analogs for extraterrestrial icy moons and their potential for habitability. Her research interest in the astrobiology of icy systems focuses on Europa, where she models the formation of surface terrain to better understand ice-ocean interactions and works on a variety of instrument technology and platforms for subsurface exploration. Dr. Schmidt is also a participating scientist on NASA's Europa Clipper radar team, a member of the Europa Lander and LUVOIR science definitions teams, and an associate of the Dawn mission. She was previously a postdoctoral fellow at the University of Texas at Austin, where she was named outstanding early career researcher. She is recipient of a NASA Early Career Fellowship and the Eric R. Immel Memorial Award for Excellence in Teaching of the Georgia Tech College of Science. Dr. Schmidt earned her Ph.D. in geophysics and space physics from the University of California, Los Angeles. She has not previously served on an Academies' committee.

ROGER E. SUMMONS is the Schlumberger Professor of Geobiology at the Massachusetts Institute of Technology. His research focuses on the biogeochemistry and geobiology of microbially-dominated ecosystems, early life on the Earth, indicators of climate change, biomarkers, and terrestrial and extraterrestrial biogeochemical fossils. Dr. Summons is a fellow of the Australian Academy of Science, the Royal Society of London, the American Geophysical Union, the American Society for Microbiology and the Geochemical Society. He earned his Ph.D. in chemistry from the University of NSW, Wollongong University College. Dr. Summons has previously served on the National Academies' Committee on Astrobiology Strategy for the Exploration of Mars, Committee on the Limits of Organic Life in Planetary Sciences, and Committee on the Origins and Evolution of Life, among others.

FRANCES WESTALL is a research scientist at the Centre National de la Recherche Scientifique, where she is also director of the Exobiology Group. Dr. Westall and her laboratory lead the biosignature group of the European Space Agency's ExoMars mission Site Selection Committee and are engaged in instrument development for the in situ detection of biosignatures on extraterrestrial bodies. Her research interests include the early Earth environment and geologic context of early life, the formation of prebiotic molecules, the earliest preserved traces of life, and the search for life in the solar system. Previously, Dr. Westall conducted research in geobiology at the Universities of Nantes (France) and Bologna (Italy) and in bacterial palaeontology, prebiotic molecules, and traces of life in martian meteorites at the Lunar and Planetary Institute and NASA's Johnson Space Center. Dr. Westall has co-authored publications that have been awarded the Gerald A. Soffen Memorial Award and the WITec Paper Award. She earned her Ph.D. in marine geology from the University of Cape Town, South Africa. Dr. Westall served as a member of the Academies' Committee on the Review of MEPAG Report on Planetary Protection for Mars Special Regions.

SHELLEY A. WRIGHT is an assistant professor at the University of California, San Diego in the Center for Astrophysics and Space Sciences. Dr. Wright is an observational and experimental astrophysicist whose research concentrates on understanding how galaxies and supermassive black holes form and evolve. She is particularly engaged in the design and construction of innovative advanced, near-infrared and optical astronomical instrumentation, and she has led instrument programs at the Lick and Keck Observatories. She is project scientist for the Near-Infrared Integral Field Spectrograph and Imager for AO corrected images (IRIS) on the Thirty Meter Telescope. She is also an instrumentalist for the Search for Extraterrestrial Intelligence (SETI). Previously, Dr. Wright worked as a postdoctoral fellow under the University of California Presidential Postdoctoral Fellowship and Hubble Postdoctoral Fellowship. Dr. Wright earned her Ph.D. in astrophysics from the University of California, Los Angeles. She has not previously served on an Academies' committee.

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Glossary and Acronyms

ABL	Automated Biological Laboratory
Accretion (astronomical)	the growth of a massive object by gravitationally attracting more matter, typically gaseous matter, in an orbiting accretion disk, causing the object to grow larger, hotter and more luminous.
Accretion (meteorological)	the process of accumulation of frozen water as precipitation over time as it descends through the atmosphere, the basis of cloud formation
Adaptive optics	a technology used to improve the performance of optical systems by reducing the effect of incoming wavefront distortions by deforming a mirror in order to compensate for the distortion
Aeolian processes	abrasion, erosion, transportation and deposition by wind
AI	Artificial Intelligence
ALH	Allan Hills
ALMA	Atacama Large Millimeter Array
APF	Automated Planet Finder
ARC	Ames Research Center
Archean	the second geologic eon on Earth, occuring after the Hadean and lasting from 4 billion to 2.5 billion years ago
ASTERIA	Arcsecond Space Telescope Enabling Research in Astrophysics
AU	Astronomical unit, one Earth-Sun distance
Bayesian	a statistical framework in which Bayes' theorem is used to update the probability for a hypothesis as more evidence or information becomes available, e.g., the probability of X, given the presence of Y
Biosignature	a detectable sign, e.g., chemical or morphological, that supports the likelihood of the presence of life
Biosphere	the layer of a planet where life exists; the sum total of a planet's ecological systems
Carbonaceous chondrites	a rare and primitive type of meteorites. In addition to carbon, silicates, oxides, and sulfides, most contain water or minerals that have been altered in the presence of water and some contain organic compounds
Cementation	the process in which ions carried in groundwater chemically precipitate to form new crystalline minerals between sedimentary grains, thereby binding the grains together
CERN	European Council for Nuclear Research

Chemoautotroph	an organism, typically bacteria or archaea, that is able to derive energy from chemical reactions of inorganic molecules
CHNOPS	Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorus, Sulfur
Chromatography	the collective term for a set of laboratory techniques for the separation of mixtures. For example, in gas chromatography, the sample mixture is vaporized, injected into a stream of carrier gas, and is separated into its component compounds
COSPAR	Committee on Space Research
Cretaceous	the geological period ranging from 145-72 Mya, a subset of the Mesozoic era, ending with the the extinction of the non-Avian dinosaurs
Cryovolcano	colloquially known as an ice volcano, a geologic feature which erupts volatiles such as water, ammonia, or methane instead of molten rock
DDL	De-orbit, Descent and Landing systems
Diagenesis	the change of sedimentary rock during and after rock formation at temperatures and pressures less than what is required for the formation of metamorphic rocks but excludes surface alteration (weathering).
Diapirism	a type of geologic intrusion in which a more mobile and ductily deformable material is forced into brittle overlying rocks
Diurnal cycle	any pattern that recurs every 24 hours
DNA	Deoxyribonucleic acid; the genetic biopolymer of most terrean organisms
DRD	Dual Reciprocating Drilling
Dynamic habitability	the relationship between the likelihood of the presence of life, the age of the stellar system and the age of the planet. Planets may only be habitable during certain stages of their lifetime. Also known as punctuated habitability
EDL	Entry, Descent and Landing systems
E-ELT	European Extremely Large Telescope
ELT	Extremely Large Telescope
Enantiomer	one of an isometric pair of crystalline forms or chemical compounds whose molecules are a non-superimposable mirror image of the other, like right and left hands
ESA	European Space Agency
ESI	Earth Similarity Index
ESPRESSO	Echelle Spectrograph for Rocky Exoplanet and Stable Spectroscopic Observations
Eutectic	a mixture of chemical compounds or elements that have a single chemical composition that solidifies at a lower temperature than any other composition made up of the same ingredients.
EUV	extreme ultraviolet
Exoring	a ring system around an exoplanet
Fabrics	the spatial and geometric configuration of all the elements that make up a rock
FAST	Five-hundred-meter Aperture Spherical radio Telescope

FDL	Frontier Development Lab
Felsic	igneous rocks enriched in lighter elements (e.g., silicon, oxygen, aluminum, sodium, and potassium) that form feldspar and quartz
FNIH	Foundation for the National Institutes of Health
Fractionation (geochemical)	separation of a complex mixture in successive stages into fractions, each of which is enriched in one of the components of the mixture
Fractionation (isotopic)	the enrichment of one isotope, relative to another isotope, changing their ratios. Can occur during a phase transition
GCM	General circulation model
Geodynamics	a subfield of geophysics dealing with forces, torques and motions of the Earth. It applies chemistry and mathematics to the understanding of how mantle convection leads to plate tectonics and other geologic phenomena
Geosphere	the solid layers of a planet, including its core
Gibbs free energy	a measure of the maximum available work that can be derived from any system under conditions of constant temperature and pressure
GMT	Giant Magellan Telescope
GOE	Great Oxidation Event
GPR	ground-penetrating radar
GPS	Global Positioning System
GSMT	giant segmented mirror telescope
Gyr/Gya/Ga	Gigayear, one billion years
HabEx	Habitable Exoplanet Imaging Mission
Hadean	the first geologic eon on Earth, lasting from the planet's formation 4.540 billion years ago to 4 billion years ago
Halophile	an organism that thrives in salty environments
HITE	habitability index for transiting exoplanets
Homologation	any chemical reaction that converts the reactant into the next member of the homologous series. A homologous series is a group of compounds that differ by a constant unit, generally a CH2 group
HST	Hubble Space Telescope
Hydrogenation	to treat with hydrogen; a chemical reaction between molecular hydrogen and another compound or element
ICSU	International Council of Science
Informational heteropolymer	A polymer, containing more than one type of subunit, capable of encoding genetic information.
In situ	Latin for "in place," referring to an analysis where the phenomenon of study occurred, in contrast to a remote or a sample return analysis
Irradiance	See "Radiation flux." Also see "Spectral or Stellar Irradiance"

ITER	International Thermonuclear Experimental Reactor
JAXA	Japan Aerospace Exploration Agency
Jovian	pertaining to the planet Jupiter, or similar in size to a gas giant
JUICE	Jupiter Icy Moons Explorer
JWST	James Webb Space Telescope
KPF	Keck Planet Finder
LC-MS/MS	liquid-chromatography tandem mass spectrometry and mass spectrometry
LHS	Luyten Half-Second catalog
LIBS	Laser-induced breakdown spectroscopy
Lithology	the study of rocks' physical characteristics and formation
Lithosphere	the outermost shell of a rocky planet. On Earth, the lithosphere is the crust and the relatively elastic portion of the upper mantle
LSST	Large Synoptic Survey Telescope
LUVOIR	Large UV/Optical/IR Surveyor
Machine learning	a technique used in artificial intelligence computer science, in which programs are statistically trained on known data and gain the ability to correctly analyze new data
MAHLI	Mars Hand Lens Imager
Main sequence	the stage of stellar evolution in which a star spends the majority of its lifetime, characterized by gradually increasing temperature until it becomes a red giant
MALDI-TOF	matrix-assisted laser desorption/ionization time-of-flight
MARCO	Mars Cube One
MAVEN	Mars Atmosphere and Volatile Evolution mission
MEPAG	Mars Exploration Program Analysis Group
MER	Mars Exploration Rover
Metabolism	a set of chemical reactions in a cell by which food is built up (anabolism) into living protoplasm and by which protoplasm is broken down (catabolism) into simpler compounds with the exchange of energy; needed by life to maintain structure and grow
MIR/FIR	mid-infrared to far-infrared
ML	Machine Learning
MMT	Multiple Mirror Telescope
MOMA	Mars Organic Molecular Analyzer
Monomer	a subunit of a polymer, when bonded to other identical subunits
Monte Carlo methods	a computational algorithm that uses repeated random sampling to reach deterministic results
Motility	the ability of an organism to move independently

MSR	Mars Sample Return
NAI	NASA Astrobiology Institute
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering and Medicine
Neural network	a type of machine learning characterized by the presence of interconnected adjustable nodes, each which take an input and deterministically produce an output. The programmer is not necessarily able to interpret the intermediate “hidden layer” logics used by the program, as only its outputs are measurable
NExSS	Nexus for Exoplanet System Science
NIH	National Institutes of Health
Nitrile	an organic compound containing a cyanide group bound to an alkyl group
Noachian	a span in Martian geologic history approximately 4100 to 3700 Mya characterized by heavy asteroid bombardment and possibly abundant liquid water
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatory
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NSF	National Science Foundation
Nucleobase	the heterocycles (i.e., ring structures made of two elements) guanine, cytosine, adenine, and thymine that form the base pairs between the two polymers of a DNA double helix
Occultation	an event that occurs when one object is hidden by another object that passes between it and the observer. Contrast with a transit, when a smaller object passes in front of a larger one
One-lid planet	a type of tectonics thought to exist on Mars, in which a single stagnant crust sits atop the mantle, rather than the active plates on modern Earth
OPAG	Outer Planets Assessment Group
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer
OST	Origins Space Telescope
OST	Outer Space Treaty (1967)
PCR	polymerase chain reaction
PHI	Planetary Habitability Index
Photolysis	the decomposition of a chemical substance into simpler units as a result of the action of light
Photometry	the measurement of the brightness or intensity of light, as perceived by the human eye
Phyllosilicates	A family of minerals featuring parallel sheets of silicate. Examples include clays, mica, and serpentine

Piezophile	an organism adapted to living in high-pressure environments, such as hydrothermal vents
PIXL	Planetary Instrument for X-ray Lithochemistry
Polymerize	of molecules, combine to form large chains and networks
PPO	Planetary Protection Office
Proterozoic	the third geologic eon on Earth, occuring after the Archean and lasting from approximately 2.4 billion to 0.5 billion years ago. It was the last eon within the Precambrian supereon
Pseudo fossil	inorganic objects, markings, or impressions that might be mistaken for a fossil
R&A	research and analysis
Radiation flux	the flow of radiant energy per unit time onto unit area (typically measured in watts per square meter)
Radiolysis	the breakdown of molecules as a result of exposure to ionizing radiation
Raman spectroscopy	a technique for determining the composition a material by measuring the change in energy of laser light scattered off the sample
Rheology	the branch of physics that deals with the deformation and flow of matter, especially the non-Newtonian flow of liquids and the plastic flow of solids
RNA	ribonucleic acid
ROC	receiver-operator characteristic
RO	radio occultation
ROW	Roadmap to Ocean Worlds
RSL	recurring slope lineae
Saltation	from Latin saltus “jump,” a type of particle transport, occurring when loose materials are removed from a bed and carried by a fluid
Scarp	a steep slope that occurs from erosion or faulting, leaving two relatively level areas of differing elevations
Schreibersite	a iron nickel phosphide mineral with an $(Fe, Ni)_3P$ repeating unit. It is found in metallic meteorites and in only one-known location on Earth.
Seep	a place where water, usually groundwater, reaches the earth’s surface from an underground aquifer.
Serpentinization	a metamorphic process in which ultrabasic rocks react with water to create a variety of hydrous, magnesium-iron phyllosilicate minerals known collectively as serpentine. The process is endothermic and results in the liberation of hydrogen, methane, and hydrogen sulfide
SETI	Search for Extraterrestrial Intelligence
SHERLOC	Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals
SPARCS	Star-Planet Activity Research Cubesat

Spectral irradiance or stellar irradiance	the flux of radiant energy per unit area per unit frequency or unit wavelength (typically measured in watts per square meter per hertz or watts per cublic meter, respectively)
SPHERE	Spectro-Polarimetric High-Contrast Exoplanet Research
SSB	Space Studies Board
Starlight suppression	an astronomical technique which blocks the light from a star in order to see the much less luminous exoplanets orbiting it, related to the use of coronagraphs and starshades
Stellar type	a classification of a star based on characteristics such as temperature, luminosity, composition, and size. Ranges from the rare type O, the largest and hottest, to the common type M, far smaller
Stromatolites	layered growth structures formed by the trapping, binding and cementation of sedimentary grains by microorganisms, especially cyanobacteria. Stromatolites provide records of life on Earth more than 3.5 billion years ago
STXM	scanning transmission X-ray microscopy
Synchrotron radiation	the electromagnetic radiation emitted when charged particles are accelerated radially, usable as a source for x-ray spectroscopy
Taphonomic	the branch of paleontology that deals with the processes of fossilization
Technosignature	a detectable sign of technologically advanced life
TESS	Transiting Exoplanet Survey Satellite
TGO	Trace Gas Orbiter
TMT	Thirty Meter Telescope
TRAPPIST	Transiting Planets and Planetesimals Small Telescope
TRL	technological readiness level
Uniformitarianism	the foundational theory that changes in Earth's crust throughout geological history have resulted from the same continuous and uniform processes
UNOLS	University-National Oceanographic Laboratory System
USB	universal serial bus
UV	Ultraviolet
VISIR	VLT Imager and Spectrometer for mid-Infrared
VLT	Very Large Telescope
WFIRST	Wide Field InfraRed Survey Telescope
WISDOM	Water Ice and Subsurface Deposit Observation on Mars
WIYN	Wisconsin-Yale-Indiana-NOAO
XUV	x-ray ultraviolet
ZTF	Zwicky Transient Facility