Life Beyond the Solar System: Space Weather and Its Impact on Habitable Worlds

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NASA's Nexus for Exoplanet System Science (NExSS) is a research coordination network dedicated to the study of planetary habitability using a system science approach with inputs from astrophysics, Earth science, planetary science, and heliophysics. Herein, the NExSS community describes recent progress and future prospects for characterization and modeling of exoplanetary systems and technology development required to detect and identify signs of life.

Introduction.

The search of life in the Universe is a fundamental problem of astrobiology and a major priority for NASA. A key area of major progress since the NASA Astrobiology Strategy 2015 (NAS15) has been a shift from the exoplanet discovery phase to a phase of characterization and modeling of the physics and chemistry of exoplanetary atmospheres, and the development of observational strategies for the search for life in the Universe by combining expertise from four NASA science disciplines (heliophysics, astrophysics, planetary science and Earth science, HAPE community). The NASA Nexus for Exoplanetary System Science (NExSS) has provided an efficient environment for such interdisciplinary studies.

Solar flares, coronal mass ejections (CMEs) and solar energetic particles (SEPs) produce disturbances in interplanetary space collectively referred to as space weather, which interact with the Earth's upper atmosphere and cause dramatic impact on space- and ground-based technological systems [1]. Exoplanets within close-in habitable zones (HZs) around M dwarfs are exposed to extreme ionizing radiation fluxes, thus making exoplanetary space weather (ESW) effects crucial factor of habitability [2,3]. In this paper, we describe the recent developments and provide recommendations in this interdisciplinary effort with the focus on the impacts of ESW on habitability, and the prospects for future progress in searching for signs of life in the Universe as the outcome of the NExSS workshop held in Nov 29-Dec 2, 2016, New Orleans, LA.

This is one of five "Life Beyond the Solar System" white papers submitted by NExSS. The other papers are: (1) *Exoplanet Astrophysical Properties as Context for Habitability;* (2) *Technology Development Required for Future Progress;* (3) *Remotely Detectable Biosignatures;* (4) *Observation and Modeling of Exoplanet Environments.*

1. Areas of significant scientific or technological progress since publication of the NASA Astrobiology Strategy 2015

From the perspective of ESW, major developments since AS15 are the following:

A. Exoplanet Observations

1. Discovery and characterization of superflares on K-M dwarfs, their frequency and relations to spot sizes, rotation and effective temperatures [4-6].
2. Observational search for CMEs from active stars has recently started [7,8].
3. Detection and characterization of exospheres in hot Jupiters and constraints on star-planet interaction (X-ray and Extreme UV (XUV) driven evaporation) models [9].
4. Characterization of XUV fluxes from K-M dwarfs using combined HST, EUVE, Chandra and XMM-Newton data [10,11].
5. Reconstruction of Zeeman Doppler Imaging in a number of G-M dwarfs as a prerequisite to constrain space weather models [12,13].
6. Detection of radio emission from substellar objects, extending down to a mass of 12.7 +/- 1 M_{Jup}, confirming magnetic field strengths >3000 G for the latter [14].
7. Development of the capability to conduct near-continuous simultaneous monitoring of 1000s of nearby systems for radio emission (stellar CMEs, planetary auroral emissions) and optical emission (stellar flares).

B. Modeling of Stellar and Planetary Environments

1. 3D magnetohydrodynamic (MHD) multi-fluid models of stellar winds and CMEs have recently been constructed using advanced data-driven MHD tools validated and

calibrated for solar wind models [2,15-19]. These simulations suggest that fast, dense winds and powerful CMEs disturb exoplanetary magnetospheres, generate ionospheric currents, and introduce a number of effects including electron precipitation and Joule heating. **These effects need to be characterized to build a comprehensive picture of their impacts on atmospheric erosion, particularly for HZ planets orbiting M dwarfs which will be the first targets to characterize Earth-like exoplanets.**

2. 1D multi-fluid coupled hydrodynamic and kinetic models of XUV driven ion escape from exospheres of Earth-like exoplanets suggest that large XUV fluxes from active planet hosting M dwarfs stars may contribute to atmospheric erosion on geological timescales thus making exoplanets within their HZs uninhabitable [2,3]. Determining the timescales over which these stars are active and the extent of atmospheric erosion is vital for understanding exoplanet characterization and target selection with JWST.

3. 1D photo-collisional models enhanced with neutral chemistry were recently applied to model the prebiotic chemistry driven by precipitation of energetic protons due to SEPs from the young Sun and active stars [2,16,20].

C. Technology

1. Development of direct imaging techniques in the mid-infrared (IR) bands with Exo Life Beacon Space Telescope, ELBST (extended Fourier-Kelvin type stellar interferometers (FKSI) mid-IR space interferometers).

In the upcoming decade the exoplanet and astrobiology communities need to prepare and develop future mission concepts for space interferometry missions to directly image exoplanets in the near- and mid-IR around nearby solar type stars. The IR spectral region (3-28 microns) is well known for its richness of molecular features from bands of molecules such as carbon dioxide, water vapor, nitrous oxide, methane, hydroxyl and nitric oxide. Considerable technology development for mid-IR nulling interferometers began with the Keck Interferometer Nuller (KIN), and recently the LBTI that have provided the most sensitive observations to date of the luminosity function of warm debris disks in the HZs of nearby solar type stars. Testbeds for space interferometers (TPF-I/Darwin/FKSI) have also been developed in the US and Europe.

2. OST development.

The Origins Space Telescope (OST) is one of four mission concepts currently being studied by NASA in preparations for the Astrophysics 2020 Decadal Survey. It features a large (6.5 - 9 meter), cold (4 K), mid-to-far-IR telescope that will be orders of magnitude more powerful than existing facilities. OST will address this key science question by characterizing the atmospheres of Earth-size planets transiting in the HZs of mid-to-late M dwarf stars. OST will expand on the legacy of exoplanet science by obtaining high-precision transmission and emission (dayside and phase-resolved) spectra from 5 - 25 microns at a resolution R = 100 – 300. Achieving the necessary precision with this proven technique requires the design of a purpose-built instrument. Continued development of detector technology in the mid-IR is a fundamental step for the detection of biosignatures in exoplanetary atmospheres.

2. Important scientific or technological topics omitted from the NASA Astrobiology Strategy 2015 and which have seen advancement since publication of the strategy

Following the progress in our understanding space weather impacts on the Earth and Mars due to recent missions (GRACE, CHAMP, MAVEN), the exoplanetary community

[22] has initiated development of new approaches omitted from the NAS15 to characterize the impacts of ESW on close-in exoplanets around M dwarfs, including Proxima-b and TRAPPIST-1 [2,3,15,21,22].

3. Key research goals in the search for signs of life in the next 20 years

A. Planet Hosting Stars:

1. ESW models for K-M dwarfs require the following observational inputs: i. Far UV, Near-UV, XUV and radio emission fluxes; ii. Physical parameters of stellar chromospheres and coronae; iii. Surface magnetic field distribution (magnetograms).
2. Observed magnetic structures including spots and their association with flares.
3. Refine characterization of stellar ages based on a set of observables including Li, rotation, CaII H&K, patterns of magnetic activity. Thus, dedicated observations of flares on K-M stars at different phases of evolution are required along with flare frequency.

B. Star-Planet Interactions:

1. Develop coupled MHD, hydrodynamic and kinetic models that describe the coupling of energy flows of planet-hosting stars, and their dissipation in magnetosphere-mesosphere exoplanetary environments. This requires a well-coordinated and funded interdisciplinary effort from HAPE community.
2. Derive thresholds on parameters of space weather from stars to make a planet habitable (atmospheric neutral and ion escape rates).
3. Characterize chemistry changes due to: FUV, XUV, stellar winds, & particles.
4. Search for radio and optical stellar CME signatures by performing extended long-term observations at lower frequencies (< 10 MHz) with space or lunar radio missions.
5. Search for planetary outflows in spectral lines of H (hot Jupiters) and nitrogen and metals (terrestrial planets) driven by powerful stellar flares from active K-M dwarfs.
6. Explore when M dwarf habitable cases actually shift beyond the ice line due to severe ESW, when combined with ameliorating internal heating, including radiogenic sources as well as tidal heating within compact multi-body TRAPPIST-1 analog systems.

C. Exoplanet Environments:

1. Explore how ionosphere-thermosphere systems respond to extreme space weather.
2. Search for N_2 through mid-IR transmission and direct imaging observations, as necessary to determine how common N_2 is within exoplanetary atmospheres.
3. Detect the chemistry of young terrestrial-type exoplanets “pregnant” with life: signatures of prebiotic chemistry.
4. Detect signatures of hydrogen-rich (primary atmospheres) of terrestrial-type exoplanets around very young planet hosting stars.
5. Understand exoplanet magnetic dynamos, mantle activity, and the interplay between volcanic/tectonic activity and the generation of Earth-like magnetic fields.
6. Explore the role exomoons play in maintaining exoplanetary magnetic dynamos? (e.g., tidal enhancement of convection vs. the possible tidal melting of inner cores.)

4. Key technological challenges in astrobiology as they pertain to the search for life in extrasolar planetary systems

A. Direct Imaging

1. The Large Binocular Telescope Interferometer (LBTI) Hunt for Observable Signatures of Terrestrial Planets (HOSTS) study has recently set new limits for exozodi detection for solar-type stars [23]. These results demonstrate the power of LBTI for vetting potential targets for future direct imaging missions such as LUVOIR or HabEx, and the importance of completing and enlarging the study in the next few years.

2. Direct imaging techniques with FKSI-type ELBST.

Ground-based prototypes demonstrating relevant technologies and obtaining important science were the Keck Interferometer Nuller, and the LBTI HOSTS project [23]. Development of mission concepts and technologies were curtailed due to budget issues in the last decade. However, recent studies of star-planet interactions, including the interaction of coronal mass ejections with the atmospheres have shown that the atmosphere of the Earth (viewed as an, NO, and other molecules [20, 24]. Exoplanetary upper atmosphers respond strongly in the mid-IR and cools through mid-IR lines of NO and CO_2 and open a new potential of mid-IR spectroscopy of exoplanet atmospheres, not only with OST, but also with future ground-based and space- or moon-based nulling interferometers [25].

5. Key scientific questions in astrobiology as they pertain to the search for life in extrasolar planetary systems

1. How can we detect spectral signatures of prebiotically important molecules highlighting fundamental prerequisites of life including nitric oxide and nitrous oxide?
2. What chemistry of the most abundant and biologically important molecules that participate in pathways producing complex sugars, amino acids, and nucleobases can be learned from the biochemistry community studying origin of life on Earth?
3. How can astrophysics inform laboratory experiments in understanding which pathways efficiently produce biologically important molecules?
4. What steps are needed to build a unified network of theorists, observers, and laboratory scientists to explore the most efficient, laboratory validated, and calibrated methodologies to characterize the biologically important molecules with the strongest spectral signatures (high signal-to-noise, low spectral resolution) of life?
5. Can vibrant/detectable biospheres exist shielded from space weather in oceans below ice shells, beyond the classical HZ (including icy moons and nomad/rogue worlds)?

6. Scientific advances that can be addressed by U.S. and international space missions and relevant ground-based activities in operation or in development

1. TESS will greatly expand the population of known potentially habitable exoplanets, some of which may be selected for characterization by JWST transit transmissions spectra to look for signs of potential biosignature gases.
2. JWST will provide mid-IR transit and eclipse spectra of exoplanets around nearby stars, particularly M and K stars with exoplanets discovered by TESS, allowing characterization of their atmospheres.
3. ELTs and other ground-based platforms will greatly expand the list of rocky planets orbiting ultracool stars and characterize the atmospheres of some of them.
4. WFIRST will demonstrate the coronagraph technology for a future direct imaging mission that would study Earth-like planets, if total mission cost can be limited.

7. How to expand partnerships (interagency, international and public/private) in furthering the study of life's origin, evolution, distribution, and future in the Universe

1. NExSS's interdisciplinary community has an opportunity to formulate well-defined complex questions that can be addressed using a systems approach. To enhance the efficiency of this approach in searching for signs of life, we must also incorporate Origins of Life/Biology methodologies into these studies.

2. The International Space Science Institute (ISSI) is an efficient model of scientific collaboration in diverse fields of space science focusing on one fundamental challenge [26]. International science conferences are another important avenue to highlight challenges in searching for signs of life. We find that having only invited talks that set the stage for breakout discussions has been a novel approach to foster collaboration. From this perspective, the NExSS sponsored ESW workshop was a useful tool to connect and unify an emerging community that brings diverse ideas and methodologies to the table.

3. The key element of collaborative efforts should be the inclusion and coordination of international mission observations, theory, and laboratory experiments to explore laboratory validated, and calibrated methodologies to find the strongest signs of life.

4. International structures should explore observational methodologies through their national agencies with participation of public-private partnerships, such as the Breakthrough Initiative. This foundation plans to develop a low-cost mission to help search for life on Enceladus and its partnership with NASA can accelerate the project.

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Expanding Public-Private Partnerships for NASA Astrobiology

Community White Paper

Submitted to the National Academies of Sciences, Engineering, and Medicine 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

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Introduction

When it comes to aerospace, the Public Private Partnership (PPP) is an evolving creature that encompasses many different types of collaborations. Traditionally, these PPPs were limited to large contracts between NASA and monolithic aerospace companies like Boeing to build and launch rockets and payloads. More recently, this has expanded to contracts with newer aerospace companies, such as SpaceX and Orbital Sciences, to service the International Space Station and fly satellites. Additionally, payments to various companies in exchange for goods and services that no longer need to be developed in-house by NASA are becoming more common.

The expansion of these PPPs to the *scientific* interests of NASA, however, is complicated by the fact that research in astrophysics, heliophysics, and the solar system is not directly and immediately profitable. The primary goal of the companies mentioned above is profit, and these companies are willing to partner with NASA because it benefits, if not sustains, their bottom line. So is there a role for meaningful PPPs in NASA science programs, in particular for astrobiology?

The answer is yes—if NASA can find a way to successfully partner with NewSpace companies, and even private individuals, whose efforts are primarily independent from government, yet also intersect with the goals of NASA's astrobiology program. For example, Planetary Resources is planning to mine near-Earth asteroids for valuable materials,[2] but much can be learned from studying the natural resources on asteroids, which are essentially left-over remnants of planet formation. Yuri Milner of the Breakthrough Initiatives has even recently expressed interest in privately funding a low-cost mission to Enceladus,[3] a key target for astrobiology due to its liquid ocean beneath an icy surface.

Recognizing the hurdles to new PPP endeavors

Public and private organizations have fundamental differences that make the implementation of a PPP challenging. For example, a difficult question is specifying who exactly has authority and control. A federal agency has an imperative to serve the interests of the nation. This is not merely a statement of an ideal but a logical inference—the entire population should be eligible to receive a benefit given that everyone pays into the system. By the same reasoning, a private organization must be accountable to its stakeholders such as investors. For public organizations, the stakeholders are citizens, whereas for private companies they may include other nationalities. Thus private and public entities may each declare an obligation to their stakeholders to maintain authority and control, and the two obligations appear to inhibit partnerships.

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[2] Nave, K. "Inside the startup that wants to mine asteroids and transform space travel forever," *Wired*, July 4, 2017.

[3] Boyle, A. "Billionaire Yuri Milner discusses his plan to look for life on Saturn moon—and his Russian connections," *GeekWire*, November 9, 2017.

Another problem is that many government programs for establishing PPPs entail bureaucracies that are *perceived* to be large, rigid, and exclusionary (e.g., not likely to support untested or rapidly evolving concepts). As a result, it is difficult to ascertain if the most timely and impactful projects are those that ultimately get funded. Quite possibly the best ideas are never submitted for consideration as a PPP and go solely to the private sector.

There are ways to manage some of these barriers, and the question at hand is how to go beyond the status quo to realize an expansion of PPPs. Some welcome news is that NASA has just demonstrated that it both recognizes these many problems and intends to diminish them: reviews and documentation have been reduced for Class D missions (<$150M), which are ideal for innovative efforts pursued by smaller industrial partners.[4] However, there is a potential to do much more across the board.

Expanding traditional PPPs to astrobiology science

The NewSpace efforts with potential to benefit astrobiology science are still in the early stages, but they are likely to become more common. It is therefore within NASA's interest to engage these private entities in order to promote synergies with, and support for, NASA's astrobiology program. Information gained from privately funded missions can lead to benefits for future NASA astrobiology missions, which have longer development times due to their greater scientific capabilities. Moreover, engaging with these private entities provides an opportunity to increase awareness about important issues such as planetary protection.

But taking advantage of these opportunities will require NASA to take more flexible approaches to its partnerships with the private sector. Because these private entities want to accomplish their missions in cheaper and faster ways than NASA, they will not be interested in traditional approaches to PPPs that involve NASA funds distributed over several distinct phases, as this process is often viewed as too restrictive, slow, and/or uncertain. Alternative approaches to PPPs must be developed.

Given that these issues are complex, unpredictable, and rapidly changing, we recommend that a group is established to: (1) study missions, capabilities, and trends in both the global NewSpace sector and within NASA and its international partners; (2) develop and suggest concepts for adapting private missions to maximize the collection of meaningful science related to NASA's astrobiology program. Its deliverables could consist of timely reports, recommendations, and innovative legal and business

[4] Foust, J., "NASA streamlines management requirements for some science missions," *SpaceNews*, January 3, 2018.

frameworks for partners to consider.[5] If private entities decide to partner with NASA to implement the suggested changes, then instead of the exchange of funds, NASA could make available its state-of-the-art facilities, such as its anechoic chambers and vibration tables, as private entities will likely want to avoid purchasing and maintaining such expensive infrastructure.

Further and Continuous Study

The opinions expressed above are limited in scope and further study that includes key stakeholders is still needed. NASA's Science Technology Mission Directorate (STMD) has already established multiple programs to enhance PPPs that are related to astrobiology *technology*,[6] and some may serve as templates for innovation in astrobiology *science* under the SMD. However, many of these STMD programs still reflect traditional NASA approaches to PPPs, and more frequent and open discourse is needed to establish NASA programs and policies that address why private partners often hesitate to work with government.

Our suggestion of establishing a group to master this process and repeat it regularly could have different forms—such as a standing committee or a think tank—to be decided by the stakeholders. A more institutional entity such as a think tank could be funded by contributions from private donors, industry, and government, yet produce independent recommendations. A standing committee might be more dynamic and focused on specific areas of science, technology, and the timely creation of PPPs.

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[5] Imagine, for example, establishing a market value for scientifically useful data collected by private missions, thus fueling a laissez faire approach to astronomical science and exploration. The group membership should represent the backgrounds of academia, government, industry, and philanthropy.

[6] https://www.nasa.gov/directorates/spacetech/programs

Geoscience and the Search for Life Beyond the Solar System

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I. Introduction

How can scientists conclude with high confidence that an exoplanet hosts life? As telescopes come on line over the next 20 years that can directly observe photons from terrestrial exoplanets, this question will dictate the activities of many scientists across many fields. The expected data will be sparse and with low signal-to-noise, which will make disentangling biosignatures from abiotic features challenging. Our Earth is not just unique in that it hosts life, it is also the only terrestrial planet with direct observations of its interior through seismic waves, and compositional evolution through field and laboratory measurements. This extensive research reveals a planet born from collisions between worlds (Canup & Asphaug, 2001), followed by a complicated biogeochemical evolution (Lyons et al., 2014). Exoplanet interiors, on the other hand, can only be constrained by the following observations: 1) photometric and spectroscopic analysis of the planet's atmosphere, 2) spectroscopic and photometric analysis of the host star, and 3) companion planet properties. From these (future) data, astrobiologists must generate plausible compositional and evolutionary models that constrain a potentially habitable exoplanet's internal properties and history, provide environmental context, and rule out geochemical explanations for any putative biosignatures. The goal of this white paper is to frame the role of geophysical and geochemical processes relevant to the search for life beyond the Solar System and to identify critical, but understudied, areas of future research.

The emerging field of "exogeoscience" is the study of how galactic, stellar system, atmospheric, and internal processes of terrestrial exoplanets affect the properties, evolution, and observable features of their surfaces and interiors. These phenomena and their couplings are central to the concept of planetary habitability, an environmental state that permits the origination and sustainment of life, because all plausible theories require a solid surface under a liquid water layer. As biospheres sit atop a tectonically active solid planet that can generate a magnetic field above the atmosphere, solid body processes are fundamental to both theoretical models (Foley & Driscoll 2016) and retrieval algorithms (Meadows et al. 2018). Yet the challenge of measuring internal properties remotely, e.g. with photometric and/or spectroscopic data from future space- and ground-based facilities, is profound: Exoplanets are too distant for robotic exploration, and solid surfaces are opaque. Without significant investment of resources in theoretical and laboratory research to understand the full range of interior processes on exoplanets, interpreting spectral features as biosignatures will be purely speculative. Below we describe the current state of exogeoscience, and then suggest research initiatives that could dramatically improve the chances of unambiguously identifying active biology on an exoplanet.

II. Current Observations

Earth observations and analyses span field investigations, lab experiments, and theoretical work. A proper summary of Earth science is too long to review in this format, but Earth, suffice to say, is an extremely complex system with an equally complex history that is still being pieced together by geophysicists, geochemists, planetary scientists, atmospheric scientists and astrophysicists. This effort must advance beyond explaining Earth data in order to develop general principles that can be used to explain – and ultimately predict – observations from exoplanets that differ from Earth in mass, size, and chemical makeup.

Terrestrial exoplanets have been found orbiting a wide range of stars with a wide range of orbits. For stars about the size of the Sun and larger, asteroseismology can provide mass, radius and age measurements accurate to about 10% that can, in turn, provide important constraints on the bulk planet properties. Stellar spectra can provide relative abundances of elements, but isotopic abundances are only available for a small number of stars that are very similar to our Sun. Most stars form in small “embedded clusters,” but about 10% form in large clusters with nearby supernovae (Lada & Lada, 2003; Fatuzzo & Adams, 2015). The recent kilonova explosion GW081717 has shown that neutron star-neutron star mergers form significant amounts of heavy elements far from planet forming regions (Abbott et al., 2017). A recent survey of more than 1000 FGK stars in the Galaxy demonstrated a factor of two variation in the major element composition (e.g., Mg/Si and Fe/Si) of these stars (Adibekyan et al., 2015; Delgado Mena et al., 2010). These ratios determine the size of the planet’s core, the mineralogy, melting temperature, viscosity, conductivity of the mantle, storage capacity for volatiles, heat producing elements, etc. Minor elements change heating rates and crustal compositions (Unterborn et al., 2016; 2017a). Terrestrial exoplanets could have a wide range of compositions, radiogenic abundances, initial temperatures, tidal heating, and orbit in systems with orbital architectures very different from our own. An integrated, exogeoscience approach is thus needed to both assess the habitability of these planets, as well as to identify key diagnostics that differentiate inhabited, habitable, and sterile worlds.

III. The Exogeoscience Framework

The initial conditions of a terrestrial planet are set by its local environment at the time of formation, whereas the observed state of a planet is determined by its formation *and* subsequent evolution. Galactic chemical evolution increases the abundances of heavier elements, which affect molecular cloud compositions, the protoplanetary disks, and ultimately the compositions of the planets themselves. Collisions, abundances of radioactive isotopes, and tidal heating set the initial thermal state. The evolution of the planet’s interior and surface are controlled by the dynamical evolution of the interior: the movement of heat and mass through the surface, the atmosphere, and into space. Figure 1 shows a schematic of these connections. Considerable research has addressed multiple aspects of these phenomena and points toward a much greater diversity of terrestrial exoplanets than is present in our Solar System (e.g. Léger et al. 2004; Bond et al., 2010; Frank et al. 2015; Luger & Barnes 2015).

Galactic models find that heavy element abundance increases with time and proximity to the galactic center (see, e.g., Schönrich & Binney, 2009). As galactic dynamics permits stars to travel radially through the galaxy by over 10,000 light years (Sellwood & Binney, 2002), exoplanets in the stellar neighborhood may have formed in very different environments. The galactic center and supernova remnants also generate cosmic rays that may alter the atmosphere of a terrestrial exoplanet if they pass near them.

As stars form, a disk of material naturally develops around them that can produce planets. The abundances of solids depend on orbital distance, composition, temperature and pressure, which can be modified by stellar, star cluster, and protoplanet effects. Planetary migration and gravitational scattering events can significantly mix material and/or move planets large distances from their birth orbit. The disk sets the final orbital architecture of the system that sets orbital oscillation amplitudes and frequencies that then affect tidal heating and rotational braking, ultimately altering both internal and atmospheric properties.

The central star provides the largest source of energy in a planetary system and is the dominant influence on the atmosphere. The star’s composition can be extrapolated to the disk’s, thereby constraining planetary composition (Bond et al. 2010). A star’s high energy radiation and stellar wind can alter an atmosphere’s composition, possibly even removing it. The host star’s gravity can induce a torque on the planet that changes its rotation rate, and an evolving gravitational gradient across its diameter can result in tidal flexing that heats the interior. The star’s galactic orbit and composition can constrain its birth location (Loebman et al., 2016).

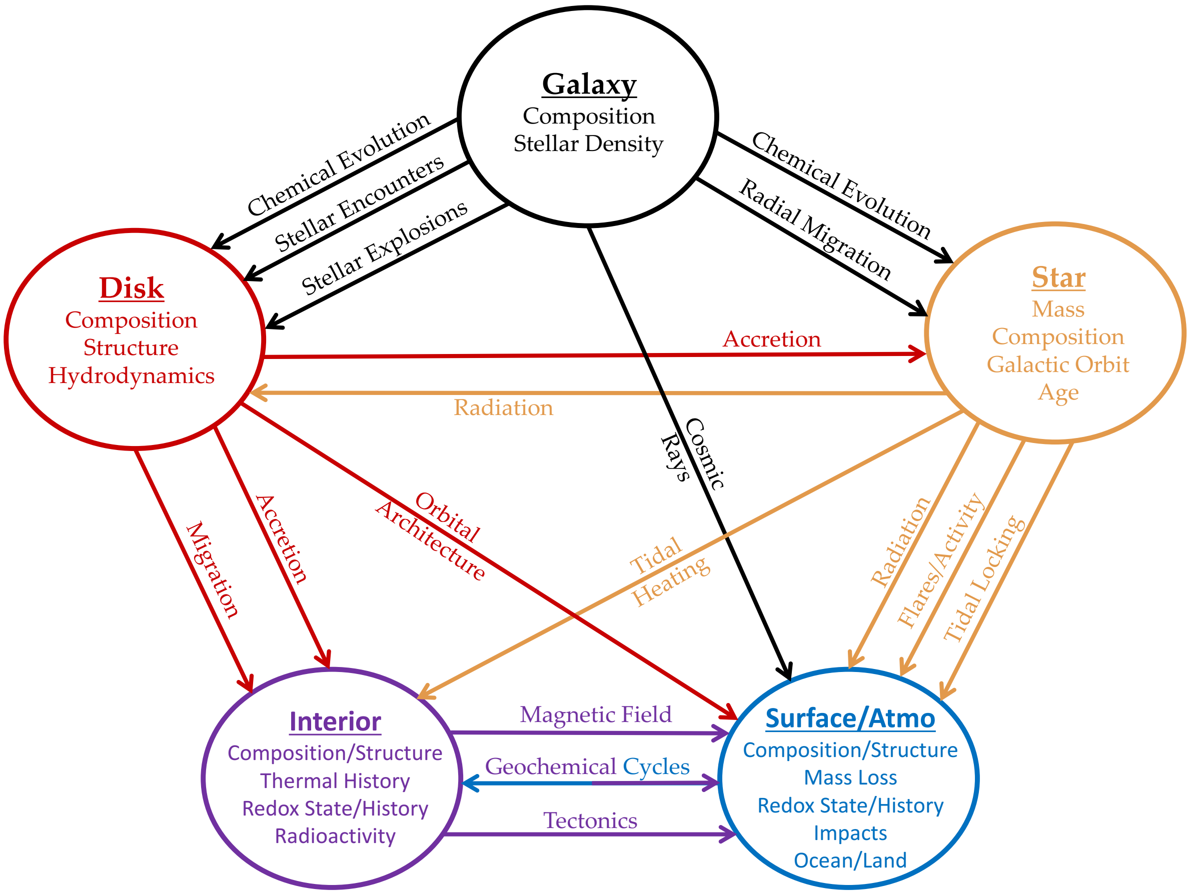

Figure 1. Schematic of connections between physical spaces (circles) and processes (arrows) that affect the compositional, thermal, and chemical evolution of terrestrial planets. Exogeoscientists must connect all these phenomena if we are to discover life on exoplanets.

The atmosphere is generated by the stellar heating of surface volatiles into the vapor phase, and by outgassing of internal volatiles. Some chemical species may be modified by stellar light (photochemistry) and others take part in chemical reactions with surface materials (geochemistry), often in complex feedback loops. The surface may be partially or completely covered in liquids. Gravitational perturbations from other planets may drive rotational and climatic cycles that change atmospheric and surface constituents.

The interior has a structure, rheology, and tectonic expression that is determined by its composition and thermal evolution. With sufficient convection in the core, a magnetic field is generated that can extend several planetary radii. Outgassing changes atmospheric composition, and eruptions provide new solid surface material for chemical alteration (weathering). Radiogenic heating, determined by primordial abundances and influenced by galactic birth environment, can provide long-lived energy sources after energy from formation has dissipated. Close-in planets may be heated to the point that solid rock is forbidden and the volatiles in the interior and atmosphere are in equilibrium.

IV. Future Prospects

Twenty years from now, spectra of hundreds of terrestrial exoplanets will be available, and the scientific community must be prepared to maximally leverage these data to constrain the planets' geophysical and geochemical processes. Ultimately, our ability to infer the formation and accumulation of biosignatures at the surfaces of these worlds – and especially in their atmospheres – will depend on our ability to compare observations with quantitative models that place constraints on the *non-biological* rates of production and destruction of these signatures. This approach can resolve the inevitable debates about "false positives", the non-biological production of putative biosignatures, as well as to avoid sinking precious observing time into planets that are likely to be "false negatives" due to high rates of non-biological consumption. Such models will inevitably be generalizations derived from our understanding of Earth's non-biological geophysics and geochemistry – an understanding that is still incomplete. Any claim for the discovery of life on an exoplanet must be predicated on a mature and robust exogeoscience, anchored to an advanced Earth system science, that can address a huge range of abiotic processes and scenarios.

Therefore, the new exogeoscience community must consist of isotope geochemists, atmospheric spectroscopists, geophysicists, planetary scientists, and galactic astronomers with expertise in observational, experimental, and theoretical methods. Success hinges on institutional support of next generation facilities and strong international collaborations. The interdisciplinary nature of the problem demands opportunities for researchers to share and synthesize ideas. Research consortia, such as NASA's NExSS, should be established to connect these communities.

Exogeoscientists must engage galactic astronomers to elucidate the roles of stellar migration, supernova, and kilonova. Reliably tracing a star's composition to its birth environment (e.g. Loebman et al. 2016) can constrain composition and the likelihood of stellar encounters (Kaib et al., 2013). Models of supernova should be improved to calculate probabilities for the injection of short- and long-lived radionuclides into protoplanetary disks (e.g. Lichtenberg et al., 2016; Fatuzzo & Adams, 2016). The new era of gravitational wave astronomy must be exploited to determine how heavy elements are produced and distributed in the galaxy.

Theoretical models must be capable of simulating plausible formation scenarios to generate initial conditions for planetary system evolution codes that can tractably predict billions of years of evolution. Formation models that self-consistently simulate the collapse of a molecular cloud into a star+disk and the subsequent evolution of that disk are still beyond current technology, but they will be essential for predicting the initial compositions and temperatures of terrestrial exoplanets. Tectonic, geochemical, and magnetic dynamo models must predict atmospheric composition and structure for arbitrary compositions and evolutionary paths. Simulating all the relevant processes will likely take hundreds of scientists and billions of hours of CPU time. Connections with new "big data" methods to handle large data volumes and high dimensional problems will likely be vital for success.

Extrapolating telescopic observations of exoplanetary atmospheres to surface conditions, crustal composition and, ultimately, habitability will require a quantitative understanding of volatile element cycling between the surfaces and interiors of these worlds. But almost all relevant experimental investigations at pressures and temperatures appropriate for planetary interiors have focused on the compositions, temperatures, and pressures of Solar System terrestrial planets (Earth abundances; <6000 K; <360 GPa). Exoplanets likely span a large compositional range and reach much higher pressures and temperatures (~4000 GPa and up to 10,000 K; Duffy et al. 2015). Based on current methodologies, a single researcher will require at least 2 years to analyze one mineral or magma composition at different pressure and temperature conditions, suggesting a thorough exploration will require dozens of people dedicated to the task for the next two decades. In order to accomplish these experiments, it is imperative they have access to a large range of experimental apparati, ranging from low-pressure piston cylinder and multi-anvil devices to high-pressure diamond anvil cells and high-powered laser-driven shock facilities. While the former three instruments are common in laboratories today, the only way to reach pressures higher than 1000 GPa is through shock compression at high-powered laser facilities, such as the magnetic pulsed power Z facility and high-powered Omega laser facilities.

The geochemical evolution of a terrestrial exoplanet over billions of years is essential information for data interpretation, but generating this timeline will be very difficult. A generalized framework for the geochemical evolution of terrestrial planets must be conceived and validated within the Solar System before being applied to exoplanets. Geochemists should be encouraged to record and even publish their “failed” ideas about Earth: Although a mechanism might not occur on Earth today because, say, its carbon abundance is too low, an exoplanet may possess that abundance and the hypothesized process may facilitate the correct interpretation of an exoplanet observation. Importantly, very little work has been done to explore the mineralogy and rock types that can be formed from melts with non-Earth compositions. Experiments that link elemental compositions, volatile solubility, and the mineralogy of mantles and crusts will be critical for establishing the supply of bioessential elements to a planet’s surface.

Geophysicists must pursue a generalized understanding of plate tectonics to develop a predictive, dynamic model. This new model must then be connected with geochemical models to understand feedback loops beyond the carbonate-silicate cycle. Weathering of crustal rocks is the key source of many bioessential elements on Earth and is likely to be an important process for exoplanets. The role of the magnetic field must also be resolved so that its presence, or lack thereof, on an exoplanet can further discriminate between sterile and biotic planets. Exo-magnetic fields will offer a unique view into the structure and dynamics of the deep interior, if and when techniques to detect them remotely become available (Driscoll & Olson, 2011).

Finally, we note that systems like TRAPPIST-1 (Gillon et al. 2017; Luger et al. 2017) could be valuable laboratories for exogeoscientists. If terrestrial (see Unterborn et al., 2017b), the inner planets are likely tidally heated, with eccentricities maintained by planet-planet perturbations, and hence are volcanically active and the atmsopheric composition traces internal composition and geophysics. Spectroscopic characterization of their atmospheres accompanied with models of highly volcanic worlds, may reveal the composition of the (less volcanically active) planets in the habitable zone. Systems with "super-Ios" and habitable zone planets may offer the best opportunity to understand the exogeoscience of potentially habitable exoplanets. Observations of such a system, accompanied with a robust exogeoscience analysis, may offer the fastest route for the detection of life on an exoplanet.

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Life Beyond the Solar System: Exoplanet Properties as Context for Planetary Habitability

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NASA's Nexus for Exoplanet System Science (NExSS) is a research coordination network dedicated to the study of planetary habitability using a system science approach with inputs from astrophysics, Earth science, planetary science, and heliophysics. Herein, the NExSS community describes recent progress toward understanding the bulk properties of exoplanets and their diversity when studied as a population. The bulk properties provide context for studies of planetary habitability and serve to focus the search for life beyond the Solar System. Next steps are described. This contribution is submitted to the National Academy of Sciences in support of the Astrobiology Science Strategy for the Search for Life in the Universe

exoplanets | astrobiology

Introduction

The search for life on planets outside our solar system has become one of the most important subjects in astrobiology. Most of the history of exoplanet research has been the province of the astrophysics community. A major development since the NASA Astrobiology Strategy 2015 document (AS15) was written has been the integration of other NASA science disciplines (planetary science, heliophysics, Earth science) with exoplanet research in the astrophysics community. The NASA Nexus for Exoplanet System Science (NExSS; https//nexss.info) has provided a forum in which scientists can collaborate across disciplines to accelerate progress in the search for life beyond the Solar System.

Herein, we describe progress and prospects for determining the bulk properties of exoplanets including, but not limited to, those orbiting in the classical habitable zone (HZ). Other aspects of exoplanet research critical for understanding planetary habitability are described in companion white papers by the NExSS community in its *Life Beyond the Solar System* series: 1) *Observation and Modeling of Exoplanet Environments*, 2) *Space Weather and its Impact on Habitability*, 3) *Remotely Detectable Biosignatures.*

Progress Since NASA's 2015 Astrobiology Strategy

Exoplanet research is a fast-paced field, with each year bringing significant new discoveries. We describe scientific milestones achieved since AS15. We make no attempt to be comprehensive of the field but rather to identify areas of significant importance to the NExSS goals of understanding planetary habitability and searching for evidence of life beyond the Solar System.

Exoplanet Populations. The study of exoplanets as a population provides big-picture insights ultimately related to planetary habitability. Besides quantifying the prevalence of potentially habitable worlds, we can better understand the domain of rocky, terrestrial planets. We can contemplate the propensity for life on planets unlike those we have in our own Solar System (e.g., super-Earths and ocean worlds). We can examine the architectures of planetary systems and better understand the role giant planets play bringing stability to terrestrial environs or wreaking havoc through dynamical interactions and migration. There are now over 600 exoplanets identified via Doppler surveys. The longevity of these surveys makes them particularly sharp probes of giant planets beyond the snow line. The realm of small planets interior to 1 AU is addressed by the transiting planets identified by Kepler [1] as shown in Figure 1.

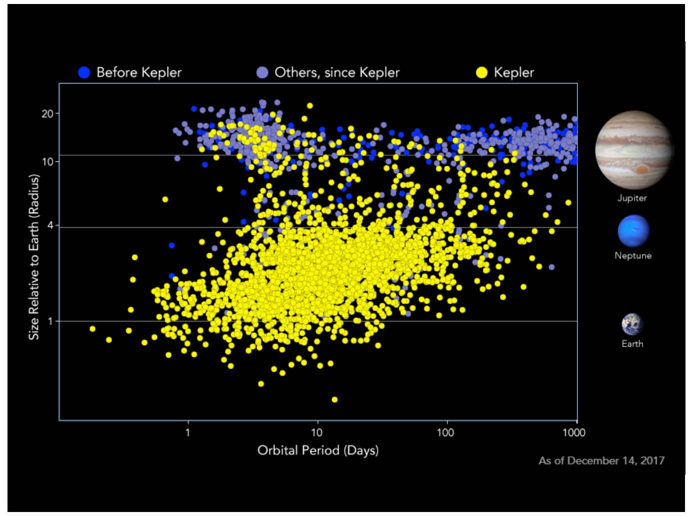

Fig. 1. Planet radius versus orbital period is plotted for the 3,567 exoplanets that have been confirmed as of December 2017 according to NASA's Exoplanet Archive.

From these surveys, we have learned about the frequency of occurrence of different types of planets. We have learned that the average number of planets per sun-like star is at least one. And there are roughly 0.25 planets within the classical habitable zone per M-type main sequence star, suggesting that the nearest such planet may be within 5 pc. Indeed, such a planet was recently identified orbiting the star nearest the star, Proxima Centauri [2]. Comprehensive reviews [3, 4] of the occurrence rate literature

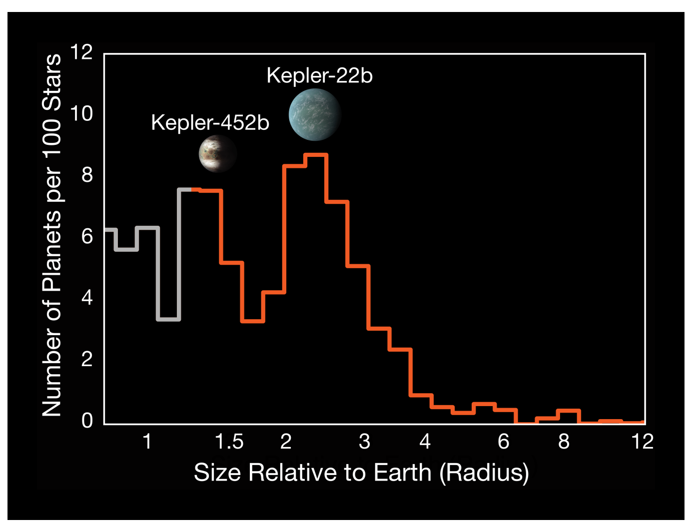

Fig. 2. The occurrence rate of exoplanets as a function of planet radius is shown for planets with orbital periods less than 100 days. The local minimum in the occurrence rate as a function of size near 1.8 $R_{\oplus}$ is suggestive of two physically distinct planet populations.

summarize the progress that's been made prior to the release of AS15.

Multiple analyses have identified a "radius valley", i.e., a local minimum in the abundance of planets as a function of planet size near 1.7–2 $R_{\oplus}$ for planets with orbital periods less than $\sim$100 days (Figure 2) [5, 6]. The valley is likely a compositional divide, with one population comprised primarily of rocky cores with thin atmospheres and the other comprised of cores enshrouded in dense atmospheres. If correct, this has significant implications for planetary habitability and future observing campaigns.

On their own, the bulk properties of an individual exoplanet say little about the complex geological and atmospheric processes required to sustain a biosphere. Assumptions of widespread 1:1 spin-orbit resonance within M dwarf HZ's have also recently been placed in doubt [7, 8]. But taken together across a population, bulk properties offer insights and provide important constraints for theoretical models of planet formation and evolution. For example, the location of the "radius valley" contains information regarding accretion and escape processes. In the standard core-accretion model, rocky cores are assembled from planetessimals until they reach sufficient mass for accreting volatile envelopes. Migration and subsequent exposure to stellar irradiation can lead to photoevaporation and envelope loss. Both accretion and evaporation rates are sensitive to the initial core mass. One plausible scenario suggested by models is that these processes corroborate to bifurcate the populations as shown schematically in Figure 3.

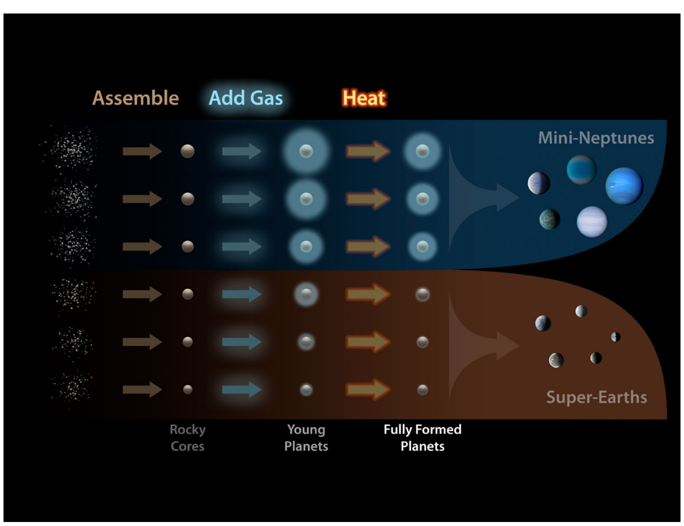

Fig. 3. Diagram illustrating how planets are assembled and sorted into two distinct size classes via accretion and photoevaporation of volatile envelopes.

Detection & Characterization of Nearby Exoplanets. Kepler identified about four dozen habitable zone planets. While the sample is valuable for statistical studies, it is not amenable to detailed characterization required to identify truly habitable environments. The mean distance to Kepler's HZ host stars is $\sim$ 300 pc. Identifying potentially habitable planets orbiting bright, nearby stars is critical for detecting the weak signals of a) the stellar reflex motion yielding planet mass and b) the atmospheric absorption lines, via transit spectroscopy or direct imaging. Identifying nearby transiting planets is one of the primary goals of the TESS Mission [9] scheduled to launch in spring 2018. In the meantime, other ground and space-based resources have made significant progress. Kepler/K2's ecliptic survey [10] and ground-based surveys like MEARTH [11, 12] and TRAPPIST [13, 14] have identified earth-size to sub-Neptune size planets orbiting relatively bright, nearby stars. Their value is underscored by the fact that they've been selected as GTO targets for first-look JWST observations[1].

Zodiacal Emission & Disk Structure. Protoplanetary disks are the raw material from which planets are built. Made from hydrogen, helium, and trace gases, plus a small fraction of fine dust, the disks somehow manage to gather up bits of rock and ice to make future habitable worlds. Temperature and pressure conditions vary with distance from the young star, governing where materials take solid form and ultimately dictating planets' compositions. Water, in particular, is ice only beyond a "snow line", that in the present-day solar system lies in the asteroid belt. Habitable planets' water may come from accreting asteroids or comets, large enough for the ices inside to survive a trip from the colder regions further out. The asteroids and comets, in turn, form by a cascade of processes leading from submicrometer grains, to pebbles big enough to fall through the gas, to bodies massive enough to come together under their own gravity. These processes control where the solid materials end up, so they decide planetary systems' starting architectures.

At the same time, flows inside protoplanetary disks move the gas and dust along gradients in both temperature and the intensity of the star's ionizing radiation, driving chemical evolution. This repartitioning of the atoms into new molecules alters the makeup of the condensible material, and thus the mix of atoms ultimately

[1] https://jwst-docs.stsci.edu/display/JSP/JWST+GTO+Observation+Specifications

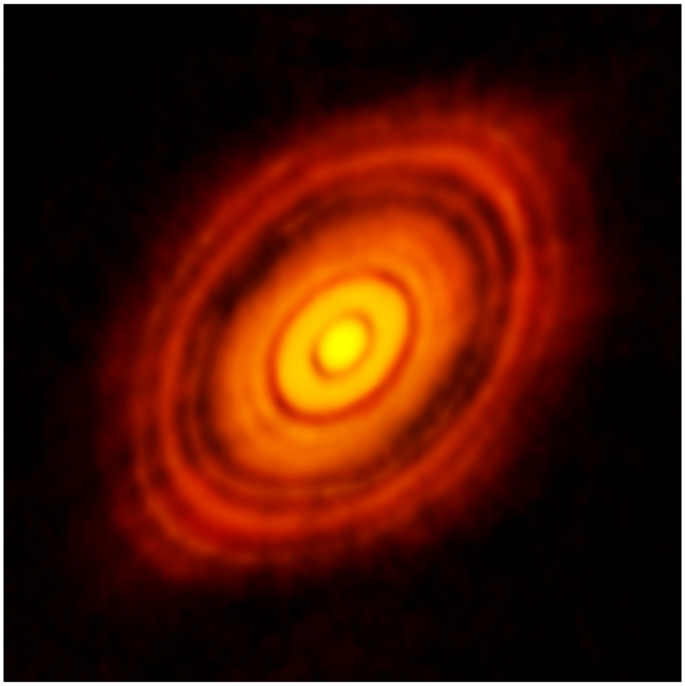

Fig. 4. ALMA observations of the disk around HL Tau show dark rings that may mark the orbits of growing planets.

available as feedstock for atmospheres, oceans, and living things.

The 2015, ALMA's sub-0.1-arcsecond spatial resolution revealed millimeter-wave emission from the protoplanetary disk around the young star HL Tau resolved into at least a half-dozen concentric bright rings [15] (Figure 4). The observation has forced us to rethink many of our assumptions about how solid material moves within protoplanetary disks. Similar structures have since been found in a half-dozen other disks, while a few instead show spiral arms. Among many ideas put forward to explain the rings are sand-grain-size aggregates losing the ices that bind them as they drift across snow lines, secular gravitational instabilities that bunch up particles within the gas, and tidal forces from embedded planets too small to open obvious gaps in the gas, but big enough to push aside the grains. Clearly the rings are connected with planet formation, but it is not yet certain where they fall in the chain of events stretching from dust to planets.

ALMA has also spatially resolved some of protoplanetary disks' chemical gradients for the first time, and obtained interesting upper limits on turbulent transport. We have reached a point where some proposed planet assembly processes are ruled out in the best-observed disks. However, we are still far from predicting the planets' final compositions and orbits from given starting conditions.

The Large Binocular Telescope Interferometer (LBTI) Hunt for Observable Signatures of Terrestrial Planets (HOSTS) study recently set new limits on exo-zodiacal emission for solar-type stars [16, 17]. With ~30 stars observed, the detection rates are comparable for early and solar type stars, ranging from 60% for stars with cold dust previously detected to 8% for stars without such excess. The upper limit on Habitable Zone (HZ) dust is 13 times the solar system value (95% confidence limit) for all stars without cold dust, and 29 times the solar system value for Sun-like stars without cold dust. Upper limits for stars with no measurable excess are approximately a factor of two lower.

Where Progress is Likely in the Next 20 Years

Significant progress is expected in the next two decades owing to NASA's responsiveness to the goals laid out in the Decadal Review [18], longer-term strategic planning [19], and support at the executive and legislative levels [20]. Here, we describe some areas where significant progress is expected.

Exoplanet Populations. Though the Kepler prime mission finished acquiring data in 2013, its final data products were delivered in 2017. Besides the the final planet catalog, the delivery includes high fidelity measurements of survey completeness and reliability. This will lend higher confidence to occurrence rate studies in the future.

One remaining challenge is the uncertainty in the planet properties. This stems from incomplete knowledge of their host stars and contamination from unknown, nearby stars. Meticulous stellar characterization is required. ESA's Gaia mission will provide parallax measurements for

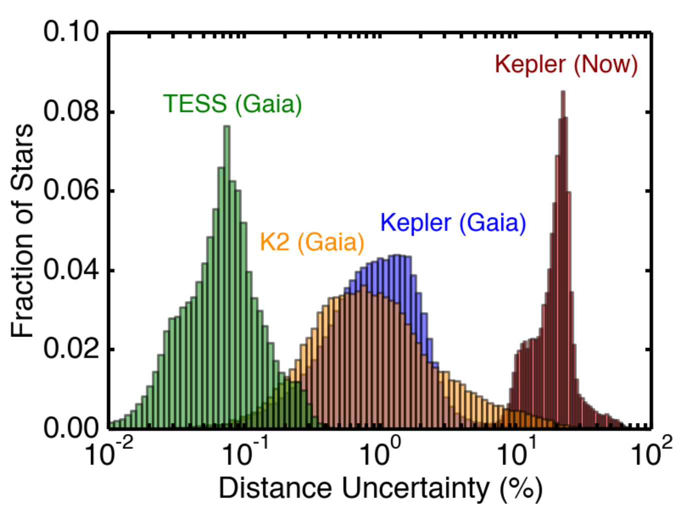

Fig. 5. Our knowledge of Kepler and TESS targets will be greatly enhanced by Gaia parallaxes.

all Kepler target stars. Data Release 2 is scheduled for Spring 2018. Based on performance metrics from Data Release 1 [21], the average uncertainty in the distance to Kepler host stars is expected to decrease from 20-30% to 5% (Figure 5). Similar improvements will be realized for stellar radii (computed from the distance modulus) and the planet's insolation flux. Since the habitable zone is defined by insolation flux, the occurrence of potentially habitable planets ($\eta_{\oplus}$) will be highly impacted by the Gaia data.

The coming decade will see significant improvements in the our understanding of the occurrence rates of exoplanets and planetary architectures as the data products from Kepler and complementary observing programs are fully utilized.

The WFIRST Mission will complement Kepler's survey of hot and temperate planets ($<$ 1 AU) by characterizing the frequency of cold planets ($>$ 1 AU) thereby building a complete picture of the architectures of planetary systems [22]. The mission is expected to yield thousands of planet discoveries, with a small overlap with Kepler. The overlap region will be valuable for improving the precision of occurrence rates and assessing systematics. Given that both surveys yield (or are expected to yield) small numbers of discoveries of earth-size planets orbiting near 1AU, the science team should consider investigating pathways leading to larger numbers of earth analog discoveries (e.g. biasing samples toward fields with larger Einstein ring radius [23]).

Characterization of Nearby Exoplanets. One of the primary goals of TESS is to identify transiting planets orbiting bright, nearby stars and measure their masses via follow-up analyses and observations [9]. The mission is expected to find close to two thousand planets, including about four dozen that are terrestrial-size and orbiting in the habitable zone [24]. A handful of these (2 to 7) are expected to orbit stars brighter than $K_s = 9$. Compared to the Kepler sample of HZ planets which are all associated with stars fainter than 10^{th} magnitude, this represents a boon for the characterization of temperate worlds.

Besides exploring the diversity of giant planet atmospheres, JWST will contribute to our understanding of the atmospheres and physical properties of both super-Earth-size planets ($\sim$1-1.6$R_{\oplus}$) interior to the habitable zone and sub-Neptune-size planets ($\sim$2.5-4$R_{\oplus}$) across a wide range of orbital separations. JWST is not, however, expected to provide meaningful constraints on the atmospheres of a sizable number of earth-size planets in the habitable zone, if any. Characterizing the habitability of sizable numbers of true Earth analogs will require a successor flagship mission, such as LUVOIR[25]. Methodical characterization of substantial populations (dozens to hundreds) of such planets will be essential to provide the context for interpreting observations of planets that initially seem to be most similar to Earth[26]. Performing detailed characterization of such a large sample will require finding planets around nearby stars which offer greater signal-to-noise per unit observing time. Accurate statistical inferences will be dramatically more powerful if they can draw from homogeneously selected samples. Realizing this goal would require significant coordination of large surveys, rather than an ad hoc approach of each astronomer being awarded time to observe favorite targets.

The majority of the HZ planets expected from TESS will orbit cool stars like M dwarfs. Due to the depth and frequency of their transits, these planets are amenable to characterization. This includes the 25+ meter ground-based telescopes (ELTs) that are under construction. With some luck and the right first-generation instruments, the ELTs could put us on an expedited path toward the detection of habitable environments. In addition, the proposed Origins Space Telescope, one of four possible NASA paths for a 2030's space telescope currently under study, which focuses on infrared wavelengths beyond 5 microns, could probe biosignature gases in transmission and emission for TESS planets around M dwarfs.

Zodiacal Emission & Disk Structure. In the future, ALMA will continue to have an important role in surveying disk structure in sub-millimeter to millimeter wavelengths, tracing dust grains in protoplanetary disks. New, upcoming missions will complement these studies by providing observations at other wavelengths.

The recent constrains on exo-zodiacal emission demonstrate the power of LBTI for vetting potential targets for future direct imaging missions such as LUVOIR or HabEx. They also demonstrate the importance of completing and enlarging the study in the next few years. The WFIRST Coronagraph Instrument (CGI) may provide additional information about the properties of the dust detected by LBTI for some of the sample, as the CGI instrument will observe scattered light from dust rather than thermal emission detected by the LBTI. The two measurements taken together allow for analyses of the physical properties of the dust grain including morphology and chemistry.

JWST will image protoplanetary and debris disks in near- to mid-infrared wavelengths. This will allow us to probe the warm inner regions of disks where organic molecules may form. These organic molecules could be important building blocks of life on potentially habitable planets. In addition, near-infrared imaging by JWST of light scattered from the surface of disks can reveal features such as gaps and spirals carved by embedded planets, giving direct evidence of active planet formation, migration, and planetary system architecture.

The Origins Space Telescope (OST) mission concept would measure far-infrared emission from protoplanetary disks. In this wavelength regime, we could directly measure the gas content of protoplanetary disks from deuterated hydrogen (HD), rather than relying on highly uncertain estimates of the gas-to-dust ratio in disks. OST would also be able to measure the water content of protoplanetary disks, allowing us to understand the abundance of water available for planets forming in habitable zones. As we gain a better understanding of the structure and composition of protoplanetary disks, we can better understand the initial conditions for planet formation and the potential for life to form in the universe in general.

Conclusions

The first detection of an exoplanet more than twenty years ago ushered in a decade of discovery in which each new planet was a milestone to be celebrated. Those first steps opened up a new pathway for the search for life distinct from Solar System exploration and SETI searches. The second decade of exoplanet exploration was characterized by the demographic studies enabled by the launch of NASA's Kepler Mission. It taught us that potentially habitable worlds are common and, therefore, accessible. NASA is building upon the legacy of Kepler with TESS and JWST. Together, these missions will define the third decade of exoplanet exploration as one of atmospheric characterization, especially for sub-Neptune to giant-size planets. NASA has a jump-start on the longer term future by way of its 30-year roadmap for astrophysics and the large mission concept studies. The remote detection of global biospheres on planets beyond the Solar System is no longer a pipe dream as evidenced by the concept studies in progress for LUVOIR, HabEx, and OST.

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Planetary Caves as Astrobiology Targets

A White Paper Submitted to the Space Studies Board of the National Academy of Sciences

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Motivation

Humans have looked for extraterrestrial biosignatures on the surfaces of other planets and moons. These surfaces are often exposed to conditions and processes that exceed the physical limits of life, e.g., intense cosmic radiation, impact events, and large thermal extremes, that would render difficult the preservation of biosignatures over geologic time.

Planetary caves provide protection from cosmic radiation, small-scale impact events, and have relatively stable thermal environments. These characteristics may well permit preservation of biosignatures over long periods of time and make them a prospective astrobiology target for biosignatures beyond Earth (Boston et al., 2001; Léveillé & Datta, 2010; Martins et al., 2017). A cave with natural openings offers direct access to the subsurface without drilling and deeper penetration into subsurface materials than could be obtained from a rover, landed platform, or penetrator launched from orbit. However, current technological and mechanical limitations associated with ingress and navigation make their exploration challenging.

Caves form through a number of processes, but those on the moon and Mars identified using satellite data are lava caves. On Earth, lava caves are associated with basaltic lava, a material predicted to be ubiquitous on all rocky planets. On the moon and Mars, hundreds of vertical collapse pits have been identified using a number of remote sensing approaches (Greeley, 1971; Cushing et al., 2007; Haruyama et al., 2009; 2017); many of these may be skylights providing direct access to intact caves that should be substantially larger than those found on Earth due to the combination of lower gravity and higher eruption rates on these smaller planetary bodies (e.g., Blair et al., 2017). Future planetary astrobiology missions would be well-served to include lava caves as a high-priority target for investigation.

The purpose of this white paper is to urge support for development of technology needed to enter a planetary cave with a scientific payload for deployment. In the next pages, we review the main challenges associated with: 1) identification of planetary lava caves, 2) subsurface exploration vehicles with advanced subsurface communications/operations techniques, and 3) sensor systems developed for biosignature identification. NASA's SMD currently supports several Earth-based planetary cave analog investigations through its PSTAR (Planetary Science and Technology through Astrobiology Research) program; a table summary of these efforts is also included. We conclude with mention of current and on-going technology developments both internal and external to NASA that could advance planetary cave identification, access, and exploration.

1. Identification of lava caves

Lava caves are generated from basaltic eruptions, when lava discharging from a volcanic vent or fissure forms conduits that isolate the molten flow thermally from the surface and delay its cooling as the streaming material moves down slope. Ultimately, the lava drains from the conduit, leaving behind a hollow tube. Lava caves form at the surface initially, extending from flow levees along a principal flow channel, and then evolve into near-surface features as a roof is generated; fully formed lava caves are typically less than few meters below the surface of the lava flow. Continued volcanism can lead to erosion or burial of older caves beneath younger eruptions, and lava caves and their remnants can exist at substantial (> 1 km) depths on Earth though the majority extend relatively shallow (< 100 m) depths, only. These caves are most often found through the presence of skylights, where a portion of the lava cave roof has collapsed and exposed the lava cave to the surface; skylights provide surface access to lava caves and help mark their presence.

Near-surface lava caves can be detected using a variety of techniques, including:

- Visual detection of exposed skylights using **high-resolution surface imaging methods**
- Detection of topographic irregularities to identify possible lava cave openings from **surface brightness (albedo) profiles**
- **Thermal measurements and analysis** to detect temperature contrasts between cave openings and the surrounding surface rocks
- **Ground-penetrating radar** measurements to detect the presence of shallow cavities
- **High-precision gravity methods** to detect the presence of shallow lava caves

Table 1 lists examples of recent projects that focus on lava cave identification from satellite orbit or aircraft using these remote-sensing techniques.

Table 1: Lava cave detection

Technique	Project/Mission	Key Observations	References
High-res imaging of surface openings	Lunar Reconnaissance Orbiter	Subsurface voids discovered with oblique imaging may be extensive lava cave systems, or represent collapses created as magma drained	Allen (2009); Robinson et al. (2012)
	SELENE	Discovered 65 m diameter, 80-90m vertical hole in a lava cave with a ≥370 m	Haruyama et al. (2009)
Surface brightness profiles	Laboratory experiments and modeling	Models to evaluate brightness profiles of pit craters	Jung et al. (2016)
Thermal IR	Atacama Desert, Chile; Mohave Desert, USA	Contrast between surface temperatures and near-constant cave interior temperatures	Wynne et al. (2008)
	Mars Odyssey Thermal Emission Imaging System	7 candidate cave skylights located with diam. 100-225 m and predicted minimum depths ≥68-130 m	Cushing et al. (2007)
	Mars Odyssey Thermal Emission Imaging System	Analysis of T changes of day/night for 7 cave candidates	Jung et al. (2014)
Thermal inertia	LRO Diviner Lunar Radiometer	Thermal inertia and T_{max}/T_{min} ratio maps and imaging were used to identify 4 lunar sites associated with skylights	Slank (2016)
Ground-penetrating radar	SELENE Lunar Radar Sounder	Distinctive echo patterns evidence for the existence of a lava cave – and correlated with gravity mass deficiencies detected by GRAIL	Kaku et al. (2017); Sood et al. (2016)
High precision gravity	GRAIL	Relatively large linear features detected in the vicinity of known skylights	Chappaz et al. (2017)

2. Physical Exploration of Lava Caves

A variety of robotic approaches have been proposed to overcome key obstacles related to entering and navigating inside caves, including:

- Entry from the surface down into the lava cave system through a skylight – these entrances often include a large vertical drop (> 50 m).
- Traversing an irregular floor surface and/or over large blocky obstacles.
- Operations in darkness.
- Autonomous operation and localization (out of line-of-sight to surface communications).

In addition to traditional wheeled rovers, robotic vehicles using biomimicry offer alternative locomotion in challenging subsurface terrain. Prototypes include fleets of coordinating robotic ants, butterflies, dragonflies, and spiders optimized for relay communications away from a control center. Recent cave robotic innovations are centered around a few themes, sorted by modality in **Table 2**. Robotics technologies that link perception, navigation, mapping and decision making have made great advances. This means that previously impractical approaches for exploring cave environments are near-future possibilities.

Table 2: Robotic approaches to subsurface exploration of lava caves

Robotic Modality	Description	Examples
Micro-swarms	Simple, mass-produced, redundant, teams. Dropped, shot, or hop into cave entrances. Redundancy provides parallel exploration and risk reduction. Each robot in swarm has low science capability.	Pit-bots (Thangavelautham et al., 2014), SphereX (Kalita et al., (2017)
Rovers	Drive over blocky collapse ramps to access caves. Technology includes inflatable wheels, tandem tethered teams, and pneumatic hopping. Rovers are usually limited to the ground plane but provide superior payload ratio and simple concept of operations.	Sandflea (Boston Dynamics) UZUME (Furutani, 2016), Hakuto (Walker et al., 2015)
Cable-deployed	Use tethers and cables to enter through vertical skylights. Descend via rappelling or a Tyrolean deployment. Surface tether infrastructure to surface introduces complexity but can provide power and communications for robots inside cave. Possibility to lower large payloads to skylight floors.	Axel (Nesnas et al., 2008) Cliffbot (Paulsen et al., 2005) Tyrobot (Wong et al., 2015)
Climbers	Negotiate blocky hazards and climb cave walls and ceilings with gripping limbs. Enables long-duration access to interesting features on the ceiling, but moderate payload and risky because no inherent stability.	Lemur 3 (Parness et al., 2017) Geckobots (Sitti et al., 2003)
Flyers	Fly into caves through openings. Propulsive or rotorcraft. Drones avoid all obstacles and have good vantage points at the center of voids for scientific observation. Range-limited or inefficient in thin planetary atmospheres. Limited payload capacity	CMU has NASA STMD funded cave UAV exploration project, Mars Helicopter will fly on 2020 but no plans to explore a cave.

3. Sensor systems developed for cave biosignature identification

Boston and others (2001) present a comprehensive inventory of biological techniques that are commonly used to assess biosignatures associated with microbial communities in caves, many of which are not currently feasible for a remote, robotic planetary mission. A recent science instrument suite for planetary cave exploration has been proposed by Uckert et al (2017) includes:

- Infrared reflectance spectroscopy (wavelength range includes important mineralogical and biogeochemical absorption features)
- Laser-induced breakdown spectroscopy (provides elemental composition of target)
- Scanning electron microscopy and energy dispersive X-ray spectroscopy

In addition to these sensors, the robotic system could also employ

- High-resolution imaging (to record rock surfaces and assist in navigation)
- Environmental sensors (temperature, atmospheric pressure, etc.)
- Gas sensors (detection of key species, such as methane, water, etc.)
- Spectral imaging sensors, including imaging in the deep UV to detect organic and microbial features (bioluminescence) and distinguish these from mineral coatings on rock surfaces

Most of these techniques have been or will be deployed as instrument payload on planetary missions and could be adapted for use in a subsurface environment.

4. Terrestrial natural analog studies of planetary caves

There is increasing interest in the microbiome of lava caves on Earth; studies to date have focused on microbial colony morphology and association with secondary mineralogy (Lavoie et al., 2010), 16S rDNA of bacteria (Lavoie et al., 2017; Kommedal, 2017), and identifying potential energy/chemical nutrient pathways to support microbial life. **Table 3** summarizes recent and current NASA-supported lava cave astrobiology studies that could inform future planetary investigations.

Other space agencies are preparing for future planetary cave astrobiology missions through studies in terrestrial lava caves. The Canadian Space Agency's Astrobiology Training in

Lava Tubes (ATiLT) project (PI R. Léveillé) is educating the next generation of astrobiology scientists through exercises coupling stand-off life detection instruments (LIBS, IR) with laboratory analyses of field microbe-mineral-ice samples collected at Lava Beds National Monument. The European Space Agency's PANGAEA training program is preparing astronauts to become effective partners of astrobiology scientists and mission engineers through exercises in analog settings, including lava caves (Loredana Bessone, *pers. comm.*, PANGAEA program director).

Table 3: Selected NASA-funded terrestrial analog studies of lava caves

Location	Description	References
El Mapais Nat'l Monument NM, USA Death Valley Nat'l Park CA USA	Deployed NIR and XRF spectroscopies, XRF, and Deep-UV Raman instruments on rock-climbing robot. Use of pattern recognition AI to discriminate macroscopic microbial patterns on lava cave walls.	**NASA PSTAR** Free Climber project (PI A. Parnass)
Lava Beds National Monument CA, USA	Surface GPR (ground-penetrating-radar) to detect known lava caves (simulating possible activities of the Mars2020 payload instrument RIMFAX (Radar Images for Mars Subsurface Exploration)), compare with Lidar-mapped caves. Use of hand-held instruments to study alteration mineralogy in cave interiors.	**NASA PSTAR** TubeX project (PI K. Young) Esmaeili et al. (2017); Whelley et al. (2017)
	Cave astrobiology using rover-borne spectral imaging and spectrometers. Simulates astrobiology science mission operational activities with remote team directing rover and interpreting data.	**NASA PSTAR** BRAILLE project (PI J. Blank)
Craters of the Moon National Monument ID, USA	Lidar survey of the lava cave as an analog to the exploration of pits on the Moon and Mars.	**NASA SSERVI** FINESSE project (PI J. Heldmann); Garry et al. (2017)
	Geochemical techniques to evaluate the occurrence of biological activity associated with the formation of secondary minerals in lava caves and caves. Identified bio/organic compounds associated with Na-sulfates.	**NASA EXOBIOLOGY** (PI N. Hinman) Richardson et al. (2013)

5. Future lava cave astrobiology research topics

The past decade has seen significant progress made on the detection of lava cave caves on the Moon and Mars, but new advances are needed to facilitate their exploration and characterization. The Defense Advance Research Projects Agency has announced (12/2017) underground operations as the next frontier for national technology investment; planetary cave astrobiology science could benefit greatly from rapid and significant new technology achievements spurred on by this new DARPA SubT challenge.

Below are a few of the areas of research that could be supported through current and future NASA astrobiology program initiatives. Advancements in these areas would also provide benefit toward exploration of countless other difficult terrains throughout the solar system.

Remote sensing for lava cave cave detection

- Machine learning (ML) techniques to process planetary orbital imaging data to identify lava cave skylights (Wagner et al., 2017)
- Remote sensing data fusion (such as thermal, gravity, and radar) to improve detection sensitivity of near-surface caverns
- Improved sensor technology and spectral resolution to increase skylight detection success
- Application of new computational methods for analysis of massively large data sets (planetary imagery) and quantum computing

Development of Autonomous robotics abilities for lava cave cave exploration

- Sample collection and retrieval capabilities
- Highly mobile robotic units to facilitate access into lava caves

- Sensing and control systems to facilitate autonomous characterization and navigation in subsurface environments
- A reference library of images (or chemistries) of terrestrial cave biosignatures to serve as a training set for future robotics missions with enhanced AI and ML capabilities

IMPROVEMENTS IN INSTRUMENTATION FOR AUTONOMOUS IDENTIFICATION AND CHARACTERIZATION OF BIOSIGNATURES

- Low-mass, power, and volume sample preparation and instrumental techniques capable of onboard analysis of organic molecules/compounds at low detection thresholds
- *In situ* microstructural/textural analysis capabilities of mineral surface

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Enceladus: A Review of Recent Discoveries

A White Paper Submitted to the National Academies Astrobiology Science Strategy for the Search for Life in the Universe

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Introduction

Enceladus is the only world where it has been confirmed that material is ejected into space from its global subsurface salt water ocean, a process which enables direct sampling of the ocean composition. This has allowed the Cassini mission to make discoveries about the ocean, many of which were published after the writing of the NASA Astrobiology Strategy 2015. It also makes Enceladus the easiest ocean world to investigate in the search for life elsewhere in the solar system.

Global subsurface ocean

Two independent lines of evidence demonstrate that the subsurface ocean of Enceladus is global. The most recent interpretations of Cassini gravity measurements (McKinnon 2015; Cadek et al. 2016; Beuthe et al. 2016) indicate that Enceladus' rapid spin affects its degree 2 gravity harmonics, changing the compensation depth (the depth below which all pressures are hydrostatic). The simplest explanation for this is a floating ice shell of variable thickness (Airy isostasy) atop a global ocean. Enceladus' rotation was determined by Thomas et al. (2016) to have a forced physical libration ('wobble') that is too large to be consistent with a crust grounded to the core, again implying a global ocean.

The implications of a global ocean as opposed to a regional sea are important for life. A regional sea could have been formed by an impact and might only be transient; a global ocean, on the other hand, is less likely to be short-lived.

Internal heating

So what supplies the energy dissipation for this global ocean? Orbital analyses of ground-based and Cassini observations have been used to confirm an earlier result that the equilibrium tidal dissipation rate in Enceladus is in the range of 5-15 GW (Lainey et al. 2012, 2017; Howett et al. 2011). This is much higher than the 1.1 GW that was assumed previously (Meyer and Wisdom, 2007). The new rate can easily accommodate the ~5 GW of energy estimated to be coming from the Tiger Stripe features in the south pole (Spencer et al. 2013). Exactly where within Enceladus and how the heat is generated is not clear. The classic hypothesis is frictional heating in the ice shell, but Choblet et al. (2017) recently developed a model of heat production by fluid flow in a porous core that implies hydrothermal chemistry.

A long-lived plume

The well-established connection between the Enceladus plume and the E-ring (Porco et al. 2006), along with nearly 25 years of observations from the Voyager era (Haff et al. 1983), indicate that the plume is a long-lived phenomenon. Analysis of recent Cassini images has shown that the plume appears to vary on timescales longer than diurnal, perhaps due to a ~4 year libration resonance with Dione; another ~11 year libration may also be present (Nimmo et al. 2016; Ingersoll and Ewald, 2017). The distributions of jet activity and normal stresses across the south polar terrain suggest that these are spatially correlated, and tend to be greatest where the Tiger Stripes turn to align closely with the tidal axis of Enceladus (Behounkova et al. 2015). This suggests that plume is geophysically controlled, and the distribution of jets across the surface should remain consistent on timescales shorter than ~0.01 Myr (Patthoff and Kattenhorn, 2011).

Two end-member styles of water eruption have been proposed: discrete jets (Porco et al. 2014), and broad, curtain-like eruptions of material emanating from the entire fracture (Porco et al. 2014, Spitale et al. 2015). Both are likely present (Teolis et al. 2017). Some models suggest surface deposition is dominated by the ‘curtain’ emissions, with E ring contributions mainly due to variable discrete jets (Southworth et al. 2017). The half-angle assumed for most plume models is 15º (Hansen et al. 2008, Kempf et al. 2010) and, given the distance between the Tiger Stripes, the material from the jets/curtains merges into a single plume (albeit with spatial variations – Teolis et al. 2017) at an altitude of ~45 km. Any future mission targeting the Enceladus plume would therefore have a high probability of collecting plume material in a flyby over the south polar terrain at this altitude, irrespective of whether the ground track is directly over an identified discrete jet or stripe.

Hydrothermal activity

Two key discoveries strongly support the presence of an active hydrothermal system at the ocean-core interface of Enceladus. The first is silicon-rich, nanometer-sized dust particles (stream particles) identified by Hsu et al. (2015), which are comprised of silica (SiO_2). Particles of this specific composition and limited size range (2-8 nm radius) could only have been formed from ongoing high-temperature (>90 °C) hydrothermal geochemistry. Second is the detection of molecular hydrogen (H_2) in the plume by the Cassini Ion and Neutral Mass Spectrometer (Waite et al. 2017), almost certainly a product of hydrothermal processing of rock in the core.

A recent interpretation of carbonate speciation in the plume suggests a relatively alkaline pH for Enceladus’ ocean (Glein et al. 2015), consistent with off-axis hydrothermal systems found on Earth (such as the Lost City hydrothermal field, Kelley et al. 2005) which support thriving ecosystems where microbial cycling of sulfur and methane are dominant active biogeochemical processes (Brazelton et al. 2006; Lang et al. 2010).

The building blocks of life

One groundbreaking discovery by the combined measurements of the Cosmic Dust Analyzer (CDA) and the Ion and Neutral Mass Spectrometer (INMS) aboard Cassini is the presence of complex organic macromolecular compounds in a subset of the plume ice grains (Postberg et al. 2017). As the detection of these organics is dependent on impact speed, it is likely that they are fragments of larger organic molecules beyond the CDA mass range; this is supported by fragment compounds detected in the INMS mass range (Waite et al. 2009). So the ocean of Enceladus may have the appropriate chemical inventory to enable life to subsist or originate.

Sampling cells in the plume or on the surface

The grains ejected in the plume are in the sub-micron to micron range (Postberg et al. 2011; Jones et al. 2009; Shafiq et al. 2011). Estimates from particle dynamics simulations (Juhasz and Horanyi 2002) suggest that E ring particles with diameters greater than 4 µm are likely to collide with Enceladus, and have <10 year lifetimes. Particles with the longest lifetimes, almost 30 years, have diameters of ~1.2 µm. Many microbial cells are the same size or smaller than the organic-bearing ice grains in the plume and would be accessible to flyby or orbiting spacecraft. Bacterial spores, the toughest form of life and the most likely to survive in space for long timescales (Horneck et al. 1994), have diameters that typically range from 0.5 to 2 µm (Carrera et al. 2007). Hyperthermophilic archaea have also been discovered with diameters of 0.17 to 0.30 µm (Stetter, 1999), and many of the strains of vent methanogens cultured from the Lost City hydrothermal field are around 1 µm in diameter or smaller (Baross, 2018). Bacteria and Archaea associated with hydrothermal systems and long-term survivability in space could be lofted with plume material, if they are present, and accessed by spacecraft searching for life.

Enceladus-relevant investments in the next 20 years

Understanding Enceladus as a system. Work (laboratory work, modeling, and Cassini data processing/analysis) remains to be done to fully understand the Cassini dataset and Enceladus as a whole. For example, recent work by Steel et al. (2017) suggests that racemization in the Enceladus ocean would be rapid (~10^7 years), so little to no enantiomeric excess might be expected for alpha amino acids in the plume. Therefore, life detection techniques based on chirality alone could show a false negative if one were to rely on this particular biomarker assay.

Plume flythrough architectures. Recent work has demonstrated that habitability and life detection investigations could be successfully implemented as Discovery or New Frontiers missions, using multiple, independent tests to determine if life exists in the Enceladus ocean (Lunine et al. 2015). At flyby speeds of ~5 km/s, plume grain sampling occurs at just the right speed to volatilize and ionize, but not fragment, key biomolecules for analysis using both gas and ice grain impact mass spectrometry. However, other techniques requiring more technologically-challenging liquid-based analytic techniques (Mathies et al. 2017; Bedrossian et al. 2017) would benefit from technology development of hypervelocity capture front-ends. Investment in testing chambers to simulate such conditions would enable more effective testing of instruments that target not only the Enceladus plume, but comets and potentially the Europa plume as well.

Landed mission technology. The benefits of a landed mission on Enceladus are: (1) landed missions can access the largest plume grains, which are challenging to sample safely with a flyby or orbiting mission; (2) the freshest sample is closest to the surface, and therefore easily accessible; (3) large quantities of material can be collected and analyzed; and (4) deposition is rapid enough to cover and protect 'fresh' material from alteration/ destruction by UV radiation (Porco et al. 2017). This type of architecture could be implemented as a Flagship-class mission, and investments such as the Europa Lander mission concept (Europa Lander Study, 2016) could be leveraged. While lander concepts should continue to be developed, such a design is not required to determine signs of life on Enceladus.

Sample return. For a long-duration mission such as an Enceladus sample return mission, which could require 14 years or more round-trip (7 years with the collected samples), preservation of biomarkers is paramount. Contamination is another issue, in particular if only small amounts of native materials are collected. Proper forward and backward contamination procedures should be put in place years prior to launch, such that sample analysis can be conducted after retrieval as well as ensuring samples remain representative of their original in situ environment. Enceladus sample return would represent a logical extension to the outer solar system of the sample return program by NASA, ESA, JAXA and other international partners with such capabilities.

Reaching the ocean. Any one of the three architectures described above can provide information on signs of life that we seek in the next stage of the exploration of Enceladus, but the costs and technological investment may dramatically vary. Future efforts must therefore carefully assess the science return per dollar that is appropriate for the next step. On the other hand, indications of signs of life from any one of these three mission designs begs for the definitive step of in situ measurements with a mission to sample the ocean directly, to confirm the existence of life and study its properties. The worldwide scientific community will demand this level of verification for such a bold claim. Investments in technology to reach the ocean (plume vent climbers, melt probes, etc.) and traverse the ocean (submersibles, communication through the ice shell, etc.) should be started now, so that intrepid but feasible mission concepts can be implemented in the coming decades.

Conclusions

Could Enceladus host life? Because of the accessibility of its ocean via the plume, Enceladus offers an opportunity to make enormous progress in the search for life in the Universe. Key investments in laboratory work, modeling, data processing and technology development would enable such progress over the next 20 years.

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Seeking the origins of aqueous life on Titan

A White Paper Submitted to the National Academies Astrobiology Science Strategy for the Search for Life in the Universe

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Titan: One world, many possibilities for life

Titan is unique in the Solar System in that it hosts a rich inventory of organic molecules in its atmosphere and on its surface, along with surface liquids comprised of mostly methane and ethane and also a global subsurface liquid water ocean underneath a thick icy crust. UV radiation and high-energy charged particles initiate a chemical cascade, converting atmospheric methane and nitrogen into larger hydrocarbons and more complex organics high in the upper atmosphere (Lavvas et al. 2008; Krasnopolsky 2009, 2014; Willacy et al. 2016). Some of the larger organic particles form and aggregate, growing in size and complexity (via surface chemistry) as they descend to the surface (Hörst 2017; Cable et al. 2012). Once on the surface (or entrained in the subsurface), these complex organics may continue to react, with the products being of greater astrobiological interest if this material is subsequently exposed to liquid water.

Starting materials for potential biochemistry on Titan include small but chemically complex molecules such as unsaturated hydrocarbons and nitriles. These species are capable of diverse chemical reactions (hydrolysis, nucleophilic addition, alkylation, etc.) to generate a wide variety of products bearing different functional groups, a necessary aspect of any chemically selective biological system. Tholins – one possible laboratory analogue for the larger complex organics on Titan – quickly incorporate oxygen when exposed to liquid water (Neish et al. 2008, 2009) and produce a variety of biomolecules including amino acids and nucleobases (Neish et al. 2010; Poch et al. 2012; Cleaves et al. 2014). Tholins formed with CO in the gas mixture (as on Titan) also produced these biomolecules (Hörst et al. 2012), as did a CO_2-enriched N_2/CH_4 deposit exposed to soft X-rays (Pilling et al. 2009). This work suggests that free radical chemistry in the atmosphere (Jeilani et al. 2016) can generate nucleobases directly, indicating key biomolecules may be present to some extent on Titan's surface even prior to exposure to liquid water.

While questions concerning the possibility of 'exotic' life in the hydrocarbon lakes is an exciting prospect that merits exploration (see complementary white paper by Malaska et al.), there are multiple environments where aqueous-based life could also originate or subsist on Titan for extended periods of time. Though the surface of Titan is too cold for stable liquid water (94 K), transient liquid water environments may exist in impact melts and cryolavas, which could persist for hundreds to thousands of years (Thompson and Sagan 1992; Artemieva and Lunine 2003; O'Brien et al. 2005; Neish et al. 2006). Deeper in the crust, liquid water laccoliths (Lopes et al. 2012) and the global subsurface water ocean could both provide aqueous habitats similar in pressure and temperature to those found on Earth hosting psychrophilic (cold-loving) and piezophilic (pressure-loving) organisms (Fortes, 2001).

Titan serves as a natural laboratory for studying the products of prebiotic chemistry (Neish et al. 2018). In fact, given the wide range of possible durations where water could be liquid near the surface, different water-ice reservoirs of organics that were liquid for different amounts of time before refreezing would preserve 'windows' of varying reaction periods. By sampling these reservoirs, we might peer into these frozen 'windows' in time to observe the evolution of prebiotic to (potentially) biotic chemistry. Also, short timescales allow potential testing of the possibility that the origin of life – under suitable conditions – is extremely rapid.

Diverse environments for aqueous-based life on Titan

Impact craters. Titan's current atmosphere shields the surface from smaller impactors, so any projectile that is large enough to strike the surface will generate a substantial amount of impact melt (Artemieva and Lunine 2003). This melt likely collects in the lowest parts of the crater, forming a sheet several hundreds of meters thick. Geological investigations of impact craters on

Earth suggest efficient mixing between impact melt and solid clasts (Osinski et al., 2018) and a significant fraction of Titan's organic material is expected to remain only lightly shocked in the impact cratering process (Artmieva and Lunine 2003). Thus, liquid water and organic clasts would mix on Titan following impact, making the plethora of complex surface organics available for reactions in the transient aqueous environment. Water generated by impacts may stay liquid for 10^2 to 10^6 years, depending on the crater diameter and whether the melt drains efficiently (Artmieva and Lunine 2003; O'Brien et al. 2005, Elder et al. 2012). The formation of thermally insulating clathrate hydrates could delay freezing. Further, evidence of super-heating in impact melts on Earth (El Goresy 1965) suggests that Titan's water impact melt may initially start much warmer than the liquidus, accelerating reactions in the melt pools. The 28 certain or nearly certain craters on the surface of Titan (Wood et al. 2010) should be considered primary targets for investigations of the chemical evolution of the surface of this moon (Neish et al. 2018).

Cryolavas or crustal laccolith emplacements. Some of Titan's morphological features resemble what could be a water-ice volcano (cryovolcano) similar to those observed on other icy moons (e.g., Jankowski and Squyres 1988; Showman et al. 2004). The most intriguing of these features is Sotra Patera (part of a region formerly known as Sotra Facula), which includes the deepest pit and some of the highest mountains on Titan. This region also contains a flow-like feature with a lobate edge called Mohini Fluctus that is tens of meters thick (Lopes et al. 2013). The erupted materials may be composed of ammonia-water mixtures that would be buoyant or near-neutrally buoyant and driven upwards by large-scale tectonic stress patterns (Cook-Hallet et al. 2015; Liu et al. 2016). Though this feature, if it were originally liquid, would have frozen after a few years (Davies et al. 2016), larger cryovolcanic features such as domes or emplaced laccoliths may require several hundred years to freeze completely (Neish et al. 2006; Malaska et al. 2017; Schurmeier et al. 2016). The presence of ^{40}Ar in Titan's atmosphere argues for an outgassing mechanism (Niemann et al. 2010) such as cryovolcanism. Though the timescales for prebiotic reactions to occur are somewhat shorter for cryolavas than impact melts and the reaction rates are lower due to their reduced temperatures, these regions still merit exploration. Importantly, they (1) might be 'windows' in time to observe the progress of such reactions, and (2) may be one of the few places where subsurface materials are expressed on the surface, including possible biological material. Further, as work has shown that frozen solutions containing ammonium cyanide produce pyrimidines and purines at 195 K over several decades (Miyakawa et al. 2002), these environments also allow testing of the 'cold origin of life' hypothesis.

Subsurface ocean. Models of Titan's formation predicted the presence of a substantial liquid water layer (Grasset and Sotin, 1993; Tobie et al. 2005) and Cassini observations have confirmed that a global, salty, subsurface liquid water ocean lies approximately 55-80 km below the surface (Iess et al. 2012; Beghin et al. 2012, Mitri et al. 2014). Interior models disagree over whether a deep high-pressure icy mantle separates the subsurface ocean from the rocky core, but recent work on salt partitioning coefficients suggests this ice layer would be permeable to exchange of nutrients between the core and the ocean (Journaux et al. 2017) and could be thin (Castillo-Rogez and Lunine, 2010). Therefore Titan's subsurface liquid water ocean could rival the habitability of Europa's or Enceladus' ocean, where ecosystems based on hydrothermal activity would rely on exchange between the ocean and the core. In fact, the ocean of Titan might have a ready source of organics of varying redox state, if the massive inventory of organics generated in the atmosphere and on the surface is able to enter the subsurface and mix with liquid water. Evidence of life in this ocean might be expressed on the surface via outgassing of compounds indicative of biologic processes (e.g., Fortes 2001), a lack of expected compounds, such as acetylene (Schulze-Makuch and Grinspoon 2005), or the presence of biomarkers (amino acid abundances, isotopic ratios, etc.) in cryolavas.

Recognizing aqueous-based life in an organic-saturated environment

Titan presents a unique challenge in the search for life, in that the atmosphere and surface contain organics in such abundance and variety that a positive signature for life might be hidden in the weeds. Any technique searching for biomolecules must be particularly robust against false negatives, or have a sufficiently high dynamic range so as not to saturate in the presence of abundant abiotic organic interferents. Additionally, false positives (abiotically-generated molecules utilized by life as we know it) must be discerned from a true biotic signature, if it exists. A multi-pronged approach to life detection – implementation of multiple, independent investigations searching for different types of biomarkers (McKay 2004; Lunine et al. 2015, Europa Lander SDT Report 2016) – would be particularly useful in the organic-saturated environment of Titan's surface. Development of 'front-ends' for instruments to reduce the initial sample complexity would also improve the capability of many techniques, in particular those that cannot distinguish between structural isomers. These could include physical and chemical techniques such as selective chemical derivatization or chromatography.

Titan-relevant investments in the next 20 years

Instruments. Technology development should focus on improving both remote-sensing and in situ techniques for life detection in an organic-saturated, cryogenic environment. In particular, sampling strategies that can collect and analyze a sample without altering its composition would enable unambiguous identification of organics, as opposed to piecing together a difficult picture rendered more complex due to a destructive technique (pyrolysis, hydrolysis, etc.). **We also note that any engineering developments to reach and sample the subsurface oceans of Europa or Enceladus may also apply to Titan, which should be considered just as astrobiologically relevant as these other compelling ocean worlds.**

Modeling Titan as a system. Significant work remains to be done regarding the accurate modeling of Titan's atmosphere, surface and subsurface, as well as communication between these reservoirs. The massive dataset generated by the Cassini-Huygens mission would be even more useful with the knowledge such model-facilitated insights could provide. In particular, the investigation of geophysical processes that would allow deep subsurface life to be emplaced or exposed on the surface would be highly beneficial, as they could guide future landed missions (e.g., Turtle et al. 2017) on where to look. Also understanding how organic material might be concentrated via melting/ freezing in eutectic fluids (facilitating polymerization) under Titan conditions is important as well, and whether we can identify such areas remotely as targets to explore. Such work will be interdisciplinary by nature, and require inputs from fields of geophysics, biology, glaciology, and others.

Laboratory work. Laboratory investigations continue to probe from the 'top-down' (generating tholins and determining their composition/reactivity) and from the 'bottom-up' (starting with simple mixtures of pure compounds to determine products and reaction rates). Until these two approaches meet, many of the intricacies of Titan chemistry will remain unknown. Other avenues of laboratory research should also be explored in the context of Titan, such as the chemistry of hydrothermal systems where exchange through high-pressure ice into an ammonia-rich ocean might lead to a habitable environment. Additionally, culture and characterization of gasoline-tolerant and piezophilic organisms would be particularly useful to understand the bounds of life in crustal aqueous-hydrocarbon interfaces and pressure regimes of the Titan ocean.

Conclusions

Every place we find liquid water on Earth, we find life. While Titan has exotic environments such as hydrocarbon lakes that provide testing grounds for weird life, we cannot ignore the places where 'life as we know it' could also exist. The data from Titan calls for an aqueous-based life-detection mission in its own right. Investments in instruments, laboratory work and modeling, as well as mission concepts and sampling strategies, would address key knowledge and technology gaps to enable such a mission in the next 20 years.

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White Paper
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Advancing Astrobiology Through Public/Private Partnerships:

The FDL Model

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Executive Summary

Fundamental knowledge gaps exist in our basic understanding of the origin, nature, and evolution of life on Earth, of what distinguishes abiotic from biotic processes, and the habitability potential in our Solar System and beyond. These gaps challenge our ability to positively identify biosignatures and unambiguously confirm potential discoveries. Addressing them demands the synergistic analysis of vast amounts of data from diverse scientific domains and sources, including planetary and space missions, ground-based telescopes, field and lab experiments, and theoretical modeling. It also requires to envision countless probabilistic occurrences.

Meanwhile as Artificial Intelligence (AI) and Machine Learning (ML) are developing exponentially and becoming mainstream practice across many applied technology and social sciences domains, private companies are eagerly searching for large datasets to develop and test novel data analytics and machine-learning algorithms. This combination of high dataset demand by the public sector, and the complex and multidisciplinary data analysis needs of astrobiology, brings about an outstanding potential for the development of powerful public/private partnerships.

NASA has already engaged in such a partnership in astronomy and planetary science through the *Frontier Development Lab* (FDL) [1]. FDL is an AI applied research accelerator, and a public/private partnership between NASA Ames Research Center, the SETI Institute and leading edge technology companies. Initiated two years ago, this highly successful program is an intense 8-week workshop that tackles knowledge gaps in science and technology by pairing machine learning experts from diverse backgrounds, with early career scientists. This interdisciplinary construct has proven highly successful in the development of novel and unique approaches to addressing complex research questions, leveraging advanced AI tools and vast datasets.

Here, we propose to expand this partnership to astrobiology.

The complexity of the questions at hand, the volume of data, and the depth of multidisciplinarity and synergies involved make astrobiology an ideal scientific field for the development and use of AI methods and tools. AI can provide a critical and decisive support to standard space, lab, field, and theoretical approaches, and significantly speed up breakthrough discoveries. It is already proving its worth when applied to astrobiology-related fields in discrete experiments [*e.g.*, 2-3].

The benefits of such a model for astrobiology will be multifold and immediate, as shown by the success of FDL. It will help: (a) Fulfill astrobiology basic principles [*e.g.*, 4-5]; (b) Advance the discipline faster by augmenting funding through private partnerships and enabling the fast delivery of results on key, targeted questions, and (c) Identify, through the application of AI, new fields of enquiry for astrobiology, thereby facilitating new discoveries.

1. The Challenge

As we start exploring the possibility of life beyond Earth, we paradoxically do not yet have a consensus definition for what life is, or a clear understanding of how it started on our own planet (e.g., abiogenesis, planetary exchange, panspermia) – or where (e.g., land, ocean, minerals) – and how prebiotic chemistry transitioned to biology. What the past decades have taught us, however, is that life coevolves with its environment, each modifying the other through time, either as cause or as effect. The evidence of this coevolution and mutual interactions can be found in the geological record, and in the atmosphere as biosignatures and chemical biomarkers. This evidence includes physical fossils and bioconstructs, biogenic minerals, biomolecules, chirality, isotopic compositions of carbon, nitrogen, and hydrogen in organic matter, pigments, nucleic acids, lipids, proteins, amino-acids, kerogen, photosynthetic biosignatures, but also as chemical disequilibria, and much more.

The premise is that we should be capable of unambiguously ascertaining that a physical sample, and/or sets of data, will show evidence of biological activity and cannot be the result of abiotic processes. However, as long as this certainty cannot be achieved, a definitive conclusion cannot be reached, and evidence may remain at the level of biohints. Crossing the uncertainty threshold on the questions raised by astrobiology requires simultaneous advancement on multiple scientific fronts [4-5] to enable a holistic view on how a planetary environment may shape biological architecture, and conversely how biological processes influence the environment [e.g., 6-7].

For distant planets, this process requires the prioritization of observations and the understanding of when evidence constitutes an unexplained anomaly vs. an unambiguous indicator of biological activity. Further, as the Kepler mission shows us with each new discovery, exoplanet systems and environments are diverse, and their evolution complex. As a result of their own coevolution, it can be expected that each world represents a unique set of physicochemical conditions into which the essential elements for life could have combined, and prebiotic chemistry transitioned to biology. Some of them may resemble Earth, while others may be completely alien to us, resulting in biological architectures and biosignatures that we are not prepared to onceptualize with our current knowledge, and will likely not recognize. Recent advances in unsupervised machine learning and artificial intelligence may help to enable this required “open minded” analysis with minimal assumptions and lower bias.

2. The Response: FDL – A New Public/Private Partnership Approach for Astrobiology

The field of astrobiology is broad and complex. It extends to all scales, from the elemental bricks of life to the intricate evidence resulting from feedback loops and external forces that characterize the coevolution of life and its physical environment. Vast amounts of data encompassing, *e.g.*, biology, astronomy, planetary, space, and environmental sciences, need to be brought together, thus creating an obvious opportunity for AI to help us improve understanding and accelerate new discoveries, and where a FDL-model based approach to astrobiology can help the field make unprecedented advances.

2.1 The Frontier Development Lab

The FDL program brings together emerging talents in the fields of planetary science and machine learning [1]. In the past two years, early career scientists have focused their expertise on tightly defined questions. Using new approaches in computer science, such as deep learning and machine vision, interdisciplinary teams were able to analyze large amounts of data with great accuracy and speed. As a result, they were able to rapidly advance their research and investigate different approaches, models, and alternate solutions.

The FDL program and its methodological approach to addressing questions leveraging vast datasets and machine learning tools, is highly successful and increasingly popular in the scientific, tech., and exploration communities. This is reflected in an increased demand for participation. FDL 1.0 ran for 6 weeks in 2016. Three teams of young planetary and data scientists made up of US and international participants worked together to conceive news tools, and new approaches around the Asteroid Grand Challenge. The groups focused on specific projects while interacting with guest speakers and consultants who contributed their expertise. This program provided participants with a meaningful research opportunity, and a chance to support the work of the planetary defense community. Additionally, they matured as scientists, as they developed new research networks, learned news skills, and advanced their appreciation for problem solving using a multidisciplinary approach. FDL 2.0 ran for 8 weeks in the summer of 2017, and included five project teams, each composed of 4-5 interdisciplinary PhD researchers from the planetary and data sciences, and supported by 8 core mentors and 12 part-time subject specialists. Five projects applied AI to unresolved scientific questions in the domains of long-period comets, radar 3D shape modeling, solar-terrestrial interactions, solar storm prediction, and lunar water and volatiles.

FDL provides participants with access to end users who might benefit from the research, to help guide the problem statements. This, in turn, offers the prospect of making the research immediately applicable and beneficial to real-world needs

2.2. Public/Private Partnership

As a public/private partnership between NASA Ames Research Center and the SETI Institute, FDL greatly benefits from the involvement of core project partners, who in 2017, provided an array of support services, from funding to technology and expertise, as summarized in Table 1.

Table 1. Estimate of Total Value Provided by Core Project Partners

Partners	Capital ($)	Hardware	Cloud Compute	Mentors/ Steering Team	Location	Software Services	AI Training	Speaker/ Expert	**Total ($)**
Intel	30,000		✓	✓	✓	✓	✓		**200,000**
IBM			✓	✓		✓	✓	✓	**250,000**
NVIDIA		✓		✓	✓	✓	✓	✓	**50,000**
Space Res LU	200,000								**200,000**
KX Systems	20,000		✓			✓			**30,000**
Lockheed Martin	50,000			✓				✓	**65,000**
Planetary Res.								✓	**10,000**
USC-Mascle				✓			✓		**15,000**
Miso Tech.						✓			**20,000**
Autodeck				✓	✓	✓		✓	**30,000**
Allianz								✓	**15,000**
X Prize							✓	✓	**50,000**
Google								✓	**40,000**
Verizon								✓	**10,000**
Total ($)	**300,000**	**10,000**	**400,000**	**80,000**	**20,000**	**100,000**	**50,000**	**30,000**	**990,000**

For instance, IBM and Intel provided dedicated sandboxed hosting of relevant datasets and massive cloud-based compute resources. These included state-of-the-art kits to enable quick turnaround of experiments (*e.g.*, < 1 hour for the Imagenet Benchmark – 10 million images). The teams also had the ability to run small experiments using Nvidia's latest TX2 embedded GPU. IBM and Intel provided proprietary software libraries, accounts, and analytical resources – in addition to Nvidia's free libraries. Miso Technologies gave access to their AI driven reports and papers scanning services, and Space Resources LU (Grand Duchy of Luxembourg) provided capital to fully support one team. Our partners also provided training and machine learning "101s" including guidance on use of their respective software/hardware/cloud resources, and expert guests from both AI research problem domains. Prior to start of the research phase at the SETI Institute, FDL teams spent their first week at Nvidia for an intensive AI boot camp. Teams also had access to the Autodesk *Techshop* for prototyping and making +Entire Software Suite, to the Autodesk *Gallery* for the Big Think event, and to NASA Ames special events and presentations.

The current FDL model is centered around the specific interests of NASA programs focused on science, technology, and system priorities and needs in astronomy and planetary sciences. Interdisciplinary teams are selected following a two-step application and review process [8]. Once selected, the teams participate in an accelerated research program as outlined in Table 2.

Table 2. FDL Program Structure

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	The 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. & Prototyping	The teams begin conducting machine learning experiments to identify dead-end paths and most promising approaches.
	Week 5	Prototyping & 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 & 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

2.3. Possible Approaches for Astrobiology

FDL is currently organized as a summer workshop, but is highly flexible in its structure and can be applied to astrobiology in ways that are best adapted to various programs, including:

- *A summer workshop* supported by the NASA Astrobiology program that would keep its existing structure and would add to the breadth of NASA disciplines already contributing to FDL, providing a unique training ground to early career scientists.
- *A training program for early career or career-interruption scientists* or Postdoctoral researchers, as part of the NASA Astrobiology Institute mandate.
- *A new core program* in the NASA Astrobiology portfolio, along with Exobiology, PSTARR, MATISSE, and PICASSO.
- *Astrobiology/AI Hackathons* to engage high school and college students in competitive research programs, leveraging AI to advance astrobiology research
- *A relevant approach* to solving science, technology, and system questions in relevant NASA Astrobiology calls for proposals, including the NASA Astrobiology Institute.

3. The Benefits of an FDL Approach to Astrobiology

With its multidisciplinarity and breadth of investigations, astrobiology epitomizes the ultimate partnership and challenge for AI. It carries the potential for responding to the most fundamental questions about the origin, evolution, distribution, and future of life in the universe. Responses to these questions demand a holistic analytical approach bridging countless disciplines, the development of new synergies, new intellectual frameworks, and a considerable amount of analytical time. While astrobiology has been making incremental progress since its inception, the magnitude of its endeavor requires novel analytical tools to take the giant leap necessary to go pass the uncertainty threshold in the questions of life on Earth, and beyond.

The benefits of such partnership for astrobiology will be multifold and immediate, as shown by FDL. It will help:

(1) **Fulfill astrobiology basic principles** [4-5], *e.g.*, to educate and inspire the next generation of scientists, technologists, and informed citizens; to achieve success through the close coordination of diverse scientific disciplines and programs (including space missions) and to encourage a broad societal interest in the deeper understanding of life on Earth and beyond, and the future of life on Earth and in space. We expect that growing public awareness and interest in astrobiology and AI, can give rise to strong popular support for this type of public/private partnership.

(2) **Take quantum leaps** in our understanding of the questions of life in the universe by augmenting funding through private partnerships and allowing rapid progress in the various domains of astrobiology. The FDL model is results-driven. One of its great strengths– as proven by results over the 2-year history of the program – is to engage teams of AI specialists and scientists on highly focused science/technology/system questions for short periods of time, and within weeks, to produce meaningful results and deliverables, including the development of new exploration methods, instruments, and systems.

(3) **Identify, through the application of AI, new fields of enquiry** for astrobiology by analyzing data in ways, and at speeds that cannot be achieved by conventional computational means, and as a result, **speed up new discoveries** [9].

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Bridging Strategic Knowledge Gaps in the Search for Biosignatures on Mars

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Introduction: The Current Challenge

With the search for biosignatures, the exploration of Mars is shifting from the characterization of habitability to that of a coevolution, *i.e.*, the spatiotemporal interactions of life with its environment. At present, the intellectual framework underpinning the preparation of Mars 2020 and ExoMars along with future life-seeking missions is, however, essentially the same as the one that has guided the exploration of Mars for the past 15 years [1-4]. This framework is articulated around the terrestrial analogy principle of habitability. While this principle is helpful in characterizing Mars habitability potential over time (and that of any planet), it is limiting – and potentially misleading – for the exploration of biosignatures as it focuses primarily on the spatiotemporal dynamics and general geographic distribution of environmental factors.

Coevolution synergistically considers both life and environment. As a result, it is a more effective, systemic, and dynamic approach than habitability alone for understanding how to detect, identify, and characterize (past/present) microbial habitats and biosignatures. As a result, new paths of investigations must be developed to advance our understanding of plausible coevolution models on early Mars, and to support biosignature exploration. They include (1) revisiting intellectual frameworks, theories, hypotheses, and science questions from a coevolutionary perspective; (2) injecting an ecosystem view at all levels of biosignature exploration [5] *i.e.*, spatiotemporal scales, spectral resolution, orbit-to-ground detection and identification thresholds [*e.g.*, 6-7], landing site selection, and exploration strategies; and (3) designing and deploying new mission concepts to gain a high-resolution view of environmental variability at scales that are relevant to (past/present) martian microbial habitats.

1. Coevolution as a Guiding Exploration Principle

Biological processes on Mars, if any, would have taken place within the distinct context of an irreversible early collapse of the magnetosphere and atmosphere [*e.g.*, 8], greater climate variability and gradients, and specific geographic, planetary, and astronomical characteristics. These comprise the unique constraints of a coevolution that would have separated a martian biosphere from that of Earth very early. To evaluate their full effect on biosignatures, these constraints should be envisioned within an intellectual framework that includes life as (a) an interactive agent of transformation of its environment, and (b) a piece of a dynamic system of polyextreme environmental conditions with complex loops and feedback mechanisms.

1.1 Intellectual Framework

The concept of habitability currently driving exploration defines the environmental range (astronomical, planetary) within which life, as we know it could survive. In this definition, life is regarded as a passive actor in an environment that provides (or not) water, energy, nutrients, and shelter for prebiotic and biological processes. In itself, the definition of habitability does not imply life; it simply considers environmental conditions for its emergence and sustainability.

The habitability of early Mars has now been demonstrated by 20 years of orbital and landed missions [*e.g.*, 9-12], and organic molecules detected [13-17]. The upcoming missions will test the hypothesis that life has developed on Mars and left evidence of its presence. Testing this hypothesis requires to search for traces left by two dynamic agents (life and environment) that modified each other as cause or effect [18]. As Earth shows, coevolution affects physicochemical, geochemical, and biological processes at all scales, including *e.g.*, biological architecture, metabolic activity, morphology, the mineralogy and texture of soils and sediments, topography, the atmosphere, microbial habitats, biological dispersal, biomass production and repositories, and biosignature preservation. It is, therefore, a concept essential to biosignature exploration. A coevolutionary approach to biosignature exploration allows core hypotheses and science questions to be reframed on the basis of plausible spatiotemporal synergies between life and environment, and to infer relevant spatial scales and spectral resolution. Examples include:

***Hypothesis A*: *Prebiotic and biological processes as we know them developed on early Mars*.**

Example Questions: (1) What role did environmental differences between Earth and Mars play in an early evolution of life on Mars? (2) What was the impact of unique physical features (*e.g.*, global dichotomy, high obliquity, lost magnetosphere and atmosphere, volcanic and tectonic characteristics) on the formation and spatiotemporal evolution of environmental pathways for biological dispersal, and biomass/biosignature repositories? (3) What does a comparison between the timing of early life evolution on Earth and the current environmental models for early Mars suggest about ancient habitable environments, habitat development potential, biological dispersal, biosignature preservation, detection thresholds; (4) What does the lack of obvious biosignatures at current resolution suggest about (a) the extent and duration of subaerial habitats, biomass accumulation and preservation potential, and (b) the detection and identification thresholds of integrated instrument payloads required from orbit to the ground.

***Hypothesis B: Mars developed a second, independent, and distinct genesis*.**

Example Questions: (1) What distinct biological traits (*e.g.*, metabolism, structure, size, biogeochemical cycles) could have evolved from the unique terms of a martian coevolution (astronomical, planetary, environmental, geographic, climatic, other), and (2) what distinct traces of coevolution could they have left in the geological or spectral records? For instance, how can existing datasets be searched for unique geochemical, mineralogical, textural, and biochemical markers that could have stemmed from life's adaptation to the martian polyextreme environment?

***Hypothesis C*: *Life never developed on Mars – No coevolution*.**

Example Questions: What are the critical exploratory steps to complete at the surface, subsurface, and deep underground, (and where), before such a conclusion can be reached?

1.2 Understanding Coevolution in a Polyextreme Environment

A martian coevolution would have been imprimted early by the development of a polyextreme environment [5, 19]. While the current approach to biosignature exploration considers multiple extreme factors, it often analyzes their impact individually, with limited attempts at a systemic approach, *i.e.*, the characterization of these interactions and their effects, [*e.g.*, 20-22]. Terrestrial analogs of such environments demonstrate that interactions between multiple extreme environmental factors (*e.g.*, UV radiation, thin atmosphere, aridity) generate complex loops and feedback mechanisms at various scales through combinations that may alternatively either magnify, decrease, and/or cancel their individual effects, and often override global (planetary) trends at the scale of the microbial-habitats scales [*e.g.*, 5, 19].

- *Understanding their spatiotemporal interplay, the resulting interactions with biological processes, and the resulting biogeosignatures is key to conceptualizing a martian coevolution and finding biosignatures.*

At global to regional scale, the unique complexity of Mars – including in its early geological history – resided in the relative dominance of these polyextreme factors over space and time. Some parameters declined with time (magnetosphere, atmosphere, energy), while others had distinct spatiotemporal effects depending on obliquity (*e.g.*, water, ice distribution). For example, while the loss of the atmosphere was ultimately linked to the loss of the magnetic field, weak fields play a lesser role in surface radiation doses than the loss of the atmospheric depth [*e.g.*, 22].

Changes in atmospheric shielding were therefore not only a factor of time, but also a factor of obliquity [*e.g.*, 20-21], and this unpredictability in the radiation environment was only one of many variables (*e.g.*, changes in temperature, desiccation, geochemistry and sediment texture, acidity) life had to contend with.

- *Understanding how this variability affected prebiotic and biological processes, as well as the development and footprint of microbial habitats, is critical for evaluating plausible biomass production, potential biosignature formation and preservation, and appropriate detection levels for instruments.*

At local (habitat) scale**,** the footprint and sustainability of microbial habitats in terrestrial analogs of extreme environments depend on microclimates generated by synergies between microbial (metabolic) activity and local environmental factors, which trigger unique loops and feedback mechanisms. Changing environmental conditions would have thus affected habitats in a systemic way, with modifications and/or loss in connectivity networks, formation and isolation of microniches, and the production of very localized and specific sets of ecosystem conditions.

- *Modeling plausible metabolic pathways and responses to variable polyextreme environmental factors is key for understanding adaption and survival potential of subaerial habitats over time, their spatiotemporal distribution, and biosignature formation and preservation potential.*

2. Strategic Research Goals &Mission Support

Assuming martian coevolution, the current approach to landing site selection provides limited (contextual) support for biosignature exploration. Data at relevant spatial scales and spectral resolution are only available at the three rover landing sites and, unless a mission returns to one of them [23], knowledge acquired at these sites may only be partially transferable to exploration of a new site – *i.e.*, only if sets of environmental conditions are repeated at a habitat-relevant scale, *e.g.*, sediment mineralogy, geochemistry, texture, structure, insolation, slope, moisture, other. Current knowledge gaps will not be filled by the time Mars 2020 and ExoMars launch. However, significant advances can be made and support provided to upcoming and future missions through data analysis, theoretical modeling, lab experiments, fieldwork, High End Computing (HEC), Artifical Intelligence (AI), and machine learning, including:

2.1 Loops and Feedback Mechanisms in Polyextreme Environments: Mars' ability to preserve subaerial habitats, ecotones, connectivity networks, and microbial dispersal pathways over time would have depended on fluctuating interactions between multiple environmental extremes and their relative dominance at any given time [5]. This relative dominance would have impacted the interactions between life and environment and the spatiotemporal nature (distribution, type, biochemistry, geochemistry, mineralogy, other) of biosignatures. Relative dominance must be thus characterized over geological timescales and with changing obliquities, including along a depth gradient.

- *Lab experiments and fieldwork in extreme environments that combine multiple extreme factors relevant to Mars, emphasizing the characterization of their interactions and their effects on prebiotic, biological processes, and microbial habitats should be prioritized.*
- *Libraries of bio-geosignatures resulting from these interactions (e.g., spectral, morphologic, metabolic, genomic) should be generated at integrated scales from orbit to ground to lab.*
- *Biosignature formation should be characterized through the lens of polyextreme environmental factors and their role on local scale microclimates, characteristics of*

microbial habitats (e.g. geology, morphology, mineralogy, sediment texture, structure, composition), and preservation potential.

- *HEC-based theoretical modeling using datasets from past and present missions should support the quantitative and qualitative characterization of the spatiotemporal evolution of polyextreme interactions on Mars, including through episodic changes in obliquity. Characterization should include present-day Mars.*

2.2 Coevolution, Biological Architecture, and Biosignatures: Crossing the uncertainty threshold (*i.e.* biosignature potential *vs.* confirmed biosignature) requires (a) development of knowledge on how coevolution could have shaped a martian biological architecture (*e.g.*, chemical structure, morphology, size, genetic makeup, metabolism) and its interactions with, and response to a polyextreme environment; (b) prioritization of observations, and (c) understanding of when a suite of observations constitutes an unambiguous and definitive confirmation of the presence of life. Filling the current knowledge gaps (*e.g.*, origin and nature of life, biological architecture, biosignatures) demands analysis of vast amounts of data from many scientific domains, and envisions countless probabilistic occurrences. This is an area where Artificial Intelligence (AI) and machine learning can provide a critical support for standard lab, field, and theoretical approaches and significantly speed up breakthrough discoveries.

- *HEC-based theoretical modeling can provide the systemic environmental envelop to test scenarios for an origin of life (section 1) and the spatiotemporal evolution of habitats.*
- *Coevolution models for life as we know it can be generated by exploring datasets relative to prebiotic and biotic processes known from early Earth, which can be run through the environmental models. AI and machine learning can help accelerate the identification of unique (bio-geo)signatures across past and present mission data (orbital, landed, ground-based, and space observations) and foster the discovery of patterns of interactions from biological processes unique to Mars (life as we do not know it) with the environment.*

2.3 Ecosystem Approach to Landing Site Selection and Surface Operations: A coevolution approach calls for novel integrated investigation methods and techniques at specific spatial scales, spectral resolution, and detection/identification thresholds relevant to (past/present) microbial ecosystems. Support includes:

- *Engage microbiologists, geneticists, environmental, extreme environments, and AI specialists early and at all stages: Programmatic, missions (concept and instrument payload design, science teams), and surface operations (exploration templates).*
- *Develop an integrated suite of missions and instruments that allow the identification of biogeosignatures from orbit to the ground. This requires a quantum leap in instrument capabilities and the development of novel analytical tools [e.g., 24-26]. This is critical because mission simulations in extreme environments show that orbital resolution is of limited support for Mars-relevant biosignature detection, and because finding evidence of potentially limited and scattered biomass may prove difficult from the ground alone [5].*
- *Integrate survey techniques developed in microbial ecology into surface operation templates [e.g., 27-29].*

3. Bridging Mission Concept

While our understanding of early Mars environmental evolution still has key knowledge gaps [*e.g.*,30-31], Mars today is a reflection of the past three billion years. A characterization of the high-resolution scale of variability of the environment today has yet to be undertaken.

Such a mission, completed with our knowledge of the role of climate forcing and obliquities, would provide a low-uncertainty insight into the ecological potential of Mars's surface and near surface over 75% of its history [5]. While life is not expected on the surface today, understanding present conditions, the influence of the landscape at scales and resolution that matter for microbial habitats on Mars (*e.g.,* topography, geology, texture, albedo, mineralogy, other), will help:

- *Identify surface expressions of seasonal and perennial microenvironment "hotspots" and show what microniches could have developed on the last surface oases could have developed (e.g., What to search for). These data could be transferred back into models and AI.*
- *Identify the environmental criteria/factors and scales to investigate (i.e., where and how to search, including: slope exposure, cracks in rocks, cavities in sediments, surface/atmosphere interactions, temperature, moisture, light, mineralogy, sediment texture, pH, other).*

Ultimately, this approach could become a cornerstone strategy for the exploration of Mars, as it supports three critical exploration goals: (1) the search for biosignatures, (2) human exploration (climate, weather, and activity planning), and (3) planetary protection.

4. Concluding Remarks – Beyond Mars

These areas and related SKGs identify promising key research areas, science questions, and technology challenges in the field of astrobiology. While they are presented here in the context of the exploration of Mars, coevolution, along with the questions, hypotheses, and approaches suggested here, could be regarded as primary guiding principles for the search for life in the Solar System and beyond.

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White Paper
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Mission Concept –
High-Resolution Mars Environmental Sensor Array

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Overview

Whether it is to augment the current robotic program of biosignature exploration, support future human astrobiological investigations [1], or provide key data to understand contamination, environmental data on Mars are critically important. Mars orbiters produce datasets supporting current megascale to mesoscale climate models. Rovers collect daily environmental data at discrete locations. However, rovers are mobile platforms with instrument packages that are heterogeneous from one mission to the next, and data rarely acquired at the same site daily. Pathfinder has shown that substantial temperature differences can be induced by meter-scale topographic heterogeneities. These may affect weather locally and regionally in ways that still need to be quantified and understood, particularly when thinking at scales relevant to microbial habitats. While no life is expected to survive at the surface of Mars in present-days, the study of terrestrial extreme environments show that subaerial hotspots can provide indications of subsurface to deeper surface microbial oases. Therefore, understanding environmental variability at a resolution relevant to microbial habitat scale is a critical, and currently missing element, in the strategic planning of Mars missions. The proposed mission concept calls for deployment of large numbers of small sensors, over vast areas of Mars' surface, enabling the collection of high-resolution meteorological data. Such a mission could provide key datasets that would give a profound insight into Mars past and present astrobiological potential, and help prepare for its future exploration and colonization.

1. A Strategic Mission Gap

Over the history of robotic missions to Mars, many have gathered information about the nature and state of the atmosphere. Past and ongoing rover missions provide sedimentologic and environmental data as they move along traverses. However, much of the knowledge critical to upcoming [*e.g.*, 2-3] and future exploration is still missing. Several orbiters have accumulated atmospheric datasets spanning much of the Martian globe over multiple Martian years. However, onboard instruments rarely provide information about the lowest few kilometers of the atmosphere, their local time coverage has been limited, and their spatial resolution is seldom sufficient to resolve kilometer-scale or finer atmospheric processes. In contrast, Mars rovers collect daily environmental datasets, but rovers are mobile platforms, and resulting datasets are difficult to compare. Further, the meteorological datasets acquired thus far by landed spacecraft have been limited by calibration issues, poor or intermittent sampling, low instrument sensitivity, and both mechanical and thermal contamination from the spacecraft themselves.

Missing from past, current, and planned landed missions on Mars is a suite of instruments that work synergistically to fully characterize the near-surface environments and the surface/atmosphere interactions through long-term (> 1 martian year) monitoring of atmospheric and soil/regolith conditions. This can be accomplished through measurements of parameters including: air and surface temperature, air pressure, relative humidity, wind velocity, dust loading, trace gas concentration, soil *p*H, and other environmental variables. Notably, this includes high-frequency measurements that enable quantification of turbulent fluxes governing the exchange of heat, momentum, volatiles, and dust between the surface and atmosphere. These parameters (a) determine the local microclimate, which is critical both for quantifying the preservation potential of ancient organic biomarkers and the characterization of unique conditions for present-day near surface microbial habitat potential; and (b) influence larger atmospheric circulations that drive both the broader Martian climate system and the mesoscale conditions needed to safely conduct entry, descent, and landing operations.

The need for high fidelity surface meteorology data is well-recognized in the Mars science community. For example, a white paper by Rafkin et al. [4] stated that "*the next major increase in our understanding of the near-surface environment will come from high quality systematic measurements of winds. For this reason, winds are the next higher priority for any landed meteorology payload after pressure and temperature. Surface fluxes are major forcing functions of atmospheric motions, yet very little is known about their magnitude and variability*". Further, it has been recognized that a long-lived network of environmental instruments is critical to characterizing the variability and diversity of meteorological conditions on Mars [*e.g.,* 4-6].

To fill this gap, we recommend the inclusion in the MEP of strategic planning for the design, development, and deployment of a mission concept to characterize and quantify near-surface environmental variability on Mars at high spatial resolution. An instrument suite such at this will address numerous MEPAG objectives and high-priority investigations, including those that call for detailed measurements of atmospheric and surface conditions, to identify environments with high potential for past and extant life, as well as biosignature preservation potential; to characterize the current climate state on Mars; and to gain knowledge required for designing and implementing human missions [6].

2. Science Goals and Objectives

In the search for biosignatures, early and present Mars must be conceptualized as a biosphere, and exploration should vigorously integrate an ecosystem approach to missions – an element that is direly missing today [7]. While life as we know it, cannot survive directly exposed at the surface today, research in extreme environments shows that habitats can still develop near the surface. Their evolution in such environments is predominantly dependent on local, not global factors, and highly influenced by the landscape (*e.g.,* topography, geology, texture, albedo), and its variability at microbial habitat scale. Such habitats are characterized by unique conditions at multiple scales, but particularly at the meter to micrometer scale (*e.g.,* slope exposure, cracks in rocks, cavities ancient lakebed muds, surface/atmosphere interactions such as deliquescence, UV radiation shielding, other), *e.g.,* [8-9]. At individual sites, parameters such as temperature, moisture, light, mineralogy, sediment texture, *p*H, and others, generally differ from the average regional ambient environment, and remain stable over time, for life to persist.

Further, the conditions conducive to the formation of microbial habitats, the frequency at which they fluctuate, and how they respond and evolve in time, are dictated by local factors such as energy sources, mineralogy, geochemistry of sediments, their texture, water acquisition, moisture retention; energy transfer and preservation between the habitat and the atmosphere, and shielding (e.g., from UV) and are driven by the interactions between multiple environmental factors and their relative dominance in time. At larger scale, this would involve the interplay of polyextreme environmental factors on Mars [10], but the same is true at microscale, where local environmental conditions sustaining microbial habitats, interact in an ecosystem with complex feedback loops and mechanisms. At present, there are no datasets available to start conceptualizing the nature of such interplays on Mars, nor the types of putative microbial habitats they could sustain (or might have sustained in the past). Such datasets would allow us to model the response strategies (adaptation) of microbes (*e.g.,* physicochemical, metabolic, genetic) to the interplay of these environmental extreme factors, and to start envisioning the plausible bio/geosignatures they would leave behind (biomediated minerals, pigments, morphologies, textures, other). High-resolution environmental data would also bring important information about surface erosion and the preservation of such bio/geosignatures. Surface erosion by windblown materials has likely been the dominant mechanism exposing any potential remains of biological materials in the past 3 billion years. However, the physics of particle transport and surface abrasion on Mars are not well understood, and current saltation and atmospheric models do not explain the observed morphology of mobilized particles.

Further, such datasets have critical value for the strategic planning of Mars exploration and for considerations of planetary protection. Microbes and habitats are impacted differently by sudden surface exposure or accumulation doses [*e.g.*, 11]. Exposure is rapidly lethal for microbial organisms, although temporary survival may be possible under thin layers of dust or regolith [12]. Recent results at Gale crater show that the ionizing radiation flux reaching the surface is constant and negligible [13]. Biomolecules are compromised by dose accumulation at a rate of 10 cm depth per 300 million years [14], not instant exposure. Sterilization depth may also vary depending on the mineralogical composition and structure of the subsurface [16].

High-resolution environmental arrays, strategically deployed, will dynamically map the distribution and concentration of astrobiological hotspots. They could become a cornerstone strategy for the exploration of Mars, and support three key exploration goals: (1) the search for biosignatures; (2) planetary protection through the identification and characterization of environmental hotspots below current resolution, and their relationships with respect to present and future missions; and (3) the human exploration and colonization of Mars. Data from such arrays will be critical to: (a) *site selection* prior to the deployment of a manned crew or a colony site, (b) *weather forecasting* at colony sites (*e.g.*, dust storms, dust devil formation potential, magnitude, frequency, atmosphere dynamics, particle transport, radiation environment); (c) *colony safety and maintenance* (*e.g.,* EVA planning) where particle size and shape considerations are critical to characterize dust penetration potential in spacesuit and breathing apparatus. They will also contribute to: (a) *scientific activities*, including astrobiological exploration, where local environmental data will provide critical background to put findings into perspective; (b) l*ocal resources* (*e.g.*, understanding of regolith properties for cultures, such as grain-size and shape for water circulation and retention potential, soil *p*H, other); and (c) *prevention of contamination*. Some terrestrial organisms can survive UV radiation for hours or longer, and windblown transport from a crewed habitat to sheltered areas in the Martian soil could result in contamination, where such organisms could metabolize and possibly replicate. To avoid forward contamination by wind, main paths of dispersal must be determined.

3. High-Resolution Mars Environmental Sensor Arrays

A high resolution characterization of the scales of variability of the Martian environment is an exciting and urgently needed mission concept scientifically, that can be brought on the path to launch within the next 15 years. Such a mission would involve strong public/private partnerships with industry for technology development and advanced data analytics. Instruments and systems will benefit from the current revolution in the monitoring of the terrestrial environment and foster the design, development, and testing of intelligent communication systems. Success will also require the injection of artificial intelligence (AI) into the acquisition, processing, transfer, and analysis of the vast amount of data generated by such mission. Critically, as part of an iterative process, the concept can be fully tested on Earth through precursor simulation missions in extreme environments.

3.1 Mission Concept

Arrays that can be deployed either as several modules (defining a set – typically a minimum of two modules) in close proximity at one site; or as several sets of modules, deployed in various environments, where landing locations are dictated by mission and modeling goals (e.g., latitudes, topography, geology, mineralogy, texture/albedo, other). Key minimum requirements include geographic proximity for a set of modules (≤ 1km) with, for instance, differences in topography or slope exposure, and any other factors that may generate distinct local conditions. The baseline mission would one complete martian year. Environmental data have low bandwidth budget for communication, therefore, high-resolution data sampling rate could be achieved over long periods of time for multiple datasets at multiple fixed locations.

Development and testing areas include, but are not limited to: the design of individual communication systems; onboard data acquisition and onboard processing, analysis, and data transfer. Environmental detection algorithms developed for planetary simulations [*e.g.*,17-19], and actual missions [20-21] can be improved and upgraded. These algorithms, together with novel AI tools, will be applied onboard and/or off-board, to datasets to execute pattern detection, identification of anomalies, event detection for the atmosphere (clouds, dust devil, other) and surface/near-subsurface/atmosphere interactions. New exploration methods, instrument payload packaging and systems need to be designed, developed, and field tested with a high level of environmental analogy. While there is no perfect analog to Mars on Earth, high altitude extreme environments present many of the conditions (*e.g.*, thin, unstable atmosphere, seasonal dust devil formation, aridity, high daily and seasonal temperature variability, UV radiation – including short UV, soil geochemistry, and overall geology, and high rate of evaporation) that will enable development of baseline mission requirements. Integrated field tests in such environments will also help determine optimal sampling rates and complete mission preparation.

3.2 Example Payload

The main goal of the instrument suite will be to gain knowledge of environmental processes relating to atmospheric circulation, atmosphere/surface/near subsurface interactions, microbial habitats, biological activity, and biomarker preservation. Instrument accommodation should be designed to maximize high fidelity data return, to address these scientific concerns (*e.g.*, instruments should be deployed to avoid physical or thermal interference from the lander body. An instrument suite can be composed, but not limited to:

Mission Floor: *Pressure sensor* at ≥ 1Hz to obtain variations in CO_2 abundance, ranging from seasonal to diurnal oscillations (*e.g.*, thermal tides) to those produced by mesoscale (*e.g.*, baroclinic waves), topographic, and convective processes (*e.g.*, dust devils). *Anemometer* capable of measuring wind velocities in 3 dimensions and air temperature, with a frequency ≥10Hz required to measure all fluxes, including turbulent momentum and sensible heat fluxes. The instrument package provides diurnal and seasonal wind, and temperature series. *Relative Humidity sensor* ≥1Hz, required to obtain moisture flux into and out of the surface (when combined with acoustic anemometer wind velocities).

Mission Baseline – (Includes above Floor): *Dust sensor* at 0.1Hz, measuring suspended dust concentrations, size distribution, speed and deposition rate. It provides temporal variation in dust grain size and concentration variation with flows caused by diurnal, seasonal, convective, mesoscale-related flows. In combination with the anemometer, it provides dust fluxes and wind velocity threshold for dust entrainment. *Saltation sensor* measuring speed, flux of saltating sand grains. In combination with the anemometer, it provides wind velocity threshold for sand saltation, and an estimate of surface abrasion rates. *Methane sensor*, required to identify concentration and flux of methane. In combination with the anemometer, directions to sources can be identified. *Visible/Multispectral Imager(s)* to identify surrounding terrain (*e.g.*, rock abundance/distribution, bedforms, sediment texture, composition, soil grain-size distribution), transient event (*e.g.*, saltating particles, clouds, dust devils), and optical depth of ice and dust aerosols through direct solar imaging.

Beyond Baseline – (Includes above baseline, and in priority order): *Outgoing (downward looking) longwave radiation sensor*, radiative forcing term to close energy budget; *Incoming (upward looking) longwave radiation sensor*, radiative forcing term to close energy budget. *Incoming (upward looking) shortwave radiation (insolation) sensor*, radiative forcing term to close energy budget. It can also be used to measure atmospheric optical depth (redundancy with dust sensor) and *descent profiles of air density or temperature*. This would provide a rare opportunity for atmospheric structure measurement – considered a medium priority PSAG Gap-Filling Activity. *Soil moisture*, to determine ground heat flux, and thermal inertia. *Lidar* to provide vertical profile of aerosols (dust and water ice). This is consistent with a high-priority MEPAG investigation and PSAG Gap-Filling Activity.

4. Conclusion

The proposed array can be increased in size over time, by landing additional sets of modules to cover key regions of Mars, and include basic communication assets that could be used as a starting ground system for future human exploration. Astrobiology programs such as PICASSO and MATISSE can be used to move instrument development forward; PSTAR will field test integrated systems, investigation methods, and science operations. Industry partners will contribute AI research and development alongside NASA and academic institutions, and off-the-shelf instrument components or systems developed for environmental monitoring.

From a science standpoint, such a mission will fill a critical knowledge gap. Although our understanding of early Mars in its first billion of years remains fragmented, present-day Mars is a reflection of its past 3 billion years of history. Therefore, a characterization of the high-resolution spatiotemporal scale of variability of the environment today, combined with our understanding of obliquity cycles and climate forcing, will provide an immediate, and uncertainty-free insight into the formation of potential astrobiological hotspots at Mars' surface and near-subsurface, and an end-member for an ecosystem development potential over 75 percent of its history.

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Hydrothermal Impact Crater-Lakes and the Origin of Life

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Abstract
The young Earth during the Eoarchean (~4 Ga) was dominated by violent meteoritic impacts associated with strong volcanic and hydrothermal activity. Meteorites played two distinct roles in the origin of life: exogenous delivery of key ingredients on biomolecules and endogenous synthesis at impact crater-lakes for chemical evolution. Comets and carbonaceous asteroids deposited large amount of building blocks of life and water to the primitive Earth by recurrent impacts, thus playing a vital role in the origin of life. Extraterrestrial bolide impacts were more numerous and larger during the Late Heavy Bombardment, which created thousands of impact crater-lakes with hydrothermal systems across the protocontinents. In these sequestered crater-lakes, the cosmic building blocks of life concentrated, and were churned by convective currents, producing more complex organic compounds. The chemicals and energy found in these hydrothermal crater-lakes fueled many of the chemical reactions necessary for prebiotic synthesis and the resulting emergence of life.

Building blocks of life

The building blocks of life could have their beginnings in the tiny icy grains that make up the gas and dust in the interstellar space, and those icy grains could be the key to understanding how life arose on Earth (Bernstein et al., 1999; Chyba and Sagan, 1992; Deamer et al., 2002). Comets and carbonaceous asteroids are rich in organic molecules, which are required for the emergence of life on early Earth. Recent research in space exploration and astrobiology provides strong evidence that meteorite impacts may have sparked life on early Earth. Consequently, while life itself likely arose on Earth, the building blocks of life may well have had an extraterrestrial origin. Perhaps, the important raw material needed to build life came from space, delivered by meteorites. Many of these complex, biomolecules such as lipid membranes, amino acids, nucleotides, phosphorous, and sugars have been detected in meteorites (Bernstein et al., 1999). The cosmic origin of these building blocks occurred in an unusual interstellar, freezing and zero gravity environment during the explosion of a nearby star. Complex organic molecules, precursors to life, have been detected everywhere in space, in comets, carbonaceous asteroids, and interstellar dust. Meteorite collisions that created innumerable impact craters in the Eoarchean crust inadvertently became the perfect crucibles for prebiotic chemistry, filled with cosmic water and the building blocks of life.

The crucibles of life

The geologic site of life's beginnings is one of the key tenets to discovering where and how life originated in our planet and provides crucial clue to identify habitable environments and search for life in the Solar System. The habitats of hyperthermophiles, which are the most primitive living organisms, may shed new light on the oldest ecosystems on our planet. Discovered in 1977, submarine hydrothermal vents astounded many scientists when it was discovered that the hyperthermophilic bacteria and archaea thrive in these deep, dark, anaerobic, hostile and volcanic environments. They developed the unusual ability to utilize the chemical nutrients that rise from the hot vent fluids interfacing with cooler sea water as a source of energy (McCollom and Shock 1997). Today, hyperthermophiles are found in geothermally heated subterranean rocks such as the boiling hot springs of Yellowstone National Park, hydrothermal impact crater-lakes, and submarine hydrothermal vents along the mid-ocean ridge.

Submarine hydrothermal vents are generally considered the likely habitat for the origin and early evolution of life (Baross et al. 1985; Martin and Russell 1987). Both types of submarine hydrothermal vents—acidic black smokers and alkaline Lost City—have been considered as possible cradles of life. The chemicals found in these vents and the energy they could provide could have fueled many of the chemical reactions necessary for the emergence of life. This novel habitat is too dark at the ocean floor for photosynthesis to occur, so organisms survive by chemosynthesis, whereby energy is derived from chemical reactions. The spewing gases from the hydrothermal vents entered into a complex series of far from equilibrium chemical reactions in an extremely hot, dark and highly reducing environment.

Supports of the submarine vent hypothesis are waning in recent years (Deamer, 2011). Both submarine hydrothermal vent theories—the black smokers and the Lost City—suffer from the "concentration problem" of organic compounds. The cosmic ingredients would be dispersed and diluted rather than concentrated in the vastness of the Eoarchean global ocean before they can assemble into the complex molecules of life. A sufficient concentration of reactants is difficult to imagine in the open oceans. A protective barrier of the cradle of life is needed for prebiotic synthesis. One crucial precondition for the origin of life is that comparatively simple biomolecules must have had the opportunities to form more complex molecules by segregation and concentration of chemical compounds. In open oceans, cosmic and terrestrial chemicals could not have mixed, concentrated, selected, or organized into more complex molecules, thus inhibiting prebiotic synthesis. Moreover, at deep sea, wet and dry cycles of condensation reactions mediated by sunlight for polymerization of nucleic acids and proteins would not be available (Deamer, 2011). In contrast, wet and dry cycling occurs every day on continental hydrothermal fields. The presence of the submarine hydrothermal vents as a likely incubator is difficult to explain in one-plate Eoarchean Earth. How did the submarine hydrothermal vents such as the black smokers or the Lost City originate without plate tectonics? Today they occur along or near the axis of the spreading ridge. But if the plate tectonics did not start before 3 Ga (Tang et al., 2016), there was no spreading ridge in the oceans; we have to seek alternative hydrothermal systems on land, not in ocean.

Mulkidjanian and co-workers, working on the chemical makeup of living cells, have discovered that the chemistry of modern cells provides important clues to the original environment in which life evolved (Mulkidjanian et al. 2012). It turns out that all cells contain a lot of phosphate, potassium and other metals – but hardly any sodium. In contrast, sea water is rich in sodium but deficient in potassium and phosphates. The composition of the living cell does not match that of the ocean water. On the other hand, the inorganic chemistry of cell protoplasm mirrors the environment of freshwater ponds and lakes. These authors concluded that first life began on land, not in sea. This finding challenges the widespread view that life originated in the submarine hydrothermal vents. Once life does evolve, then both black smokers and the Lost City provide ready habitats for hyperthermophiles; but these environments are not supportive of prebiotic synthesis.

Impact crater-lakes

Impact cratering was the primal force in the early history of our planet before the onset of plate tectonics. It has shaped the surface architecture, composition, and rheology of the lithosphere, and enhanced the emergence of life. Impacts on a water-rich planet like Earth or even Mars can generate hydrothermal activity—specifically, underwater areas boiling with heat and spewing chemicals. Over 20,000 hydrothermal crater-lakes (with diameters ranging from 5 km to >1000 km) dotted the Eoarchean crust, inadvertently becoming the perfect crucibles for the prebiotic chemistry of early life (Chatterjee, 2016; Cockell, 2006; Kring, 2000; Marchi et al., 2014; Osiniski et al., 2013). An attractive alternative site for life's beginnings appears to be hydrothermal crater-lakes that might have cradled life on early Earth. These hydrothermal sites are conceptually similar to the central idea of Darwin's "warm little pond" that life on Earth originated on land. The hydrothermal crater-lakes are geochemically reactive habitats, where microbial life thrives today around superheated water supporting chemosynthetic ecosystems (Farmer, 2000). The Late Heavy Bombardment (4.1 to 3.8 billion years ago) of heightened meteoritic activity on young Earth is likely the driving force for the origin of life, since it coincided with the time of the earliest biotic activity. Most probably the Early Archean crusts of the ancient Greenstone belts of Canada, Greenland, West Australia, and South Africa was heavily pockmarked by meteorite impacts like those of the Moon and Mercury; but unlike our planetary neighbors, the crater basins on Eoarchean Earth were filled with water and biomolecules, and there developed a complex network of hydrothermal systems. The chemical nature of the hydrothermal crater-lakes, with their neutral pH and high K^+/Na^+ ratio, resembles the living cell's cytoplasm more closely than that of the submarine hydrothermal vents (Mulkidjanian et al. 2012). There are striking parallels between the chemistry of the living cell's cytoplasm, present in terrestrial hydrothermal systems, and the core energy metabolic reactions of some modern microbial communities. These hydrothermal systems did not require mid-ocean ridges and implicitly, the operation of plate tectonics.

During the Eoarchean, the Greenstone belts with thousands of hydrothermal crater-lakes were the ideal location for biosynthesis (Fig. 1). Interstellar particles, micrometeorites, small comets, and chondrites were suitable carriers for the safe delivery of the cosmic biomolecules to these crater-lakes. Earth's young atmosphere slowed down these carriers of life's first building blocks like fine dust as they lightly settled upon the crater surface. These crater-lakes became enriched with cosmic ingredients and were mixed by the convection current of the hydrothermal systems to form a concentrated, prebiotic soup. Inside the crater basin, the hydrothermal vent provided a continuous stream of chemical compounds and energy, which were mixed with cosmic ingredients by convection current to form sticky, brownish, primordial prebiotic soup. Hydrothermal crater vents provided the selection, concentration, and organization of specific organic molecules into successively more-information-rich biopolymers, and finally to the first. The transition from chemistry to biology inside the hydrothermal crater-lakes occurred around 4 billion years ago. We propose that life originated in a neutral pH milieu of terrestrial, hydrothermal crater-lakes where the building blocks of life, derived from meteorite impacts, began to concentrate, interact, and encapsulated to initiate a molecular symbiosis in an RNA/protein world (Chatterjee, 2016).

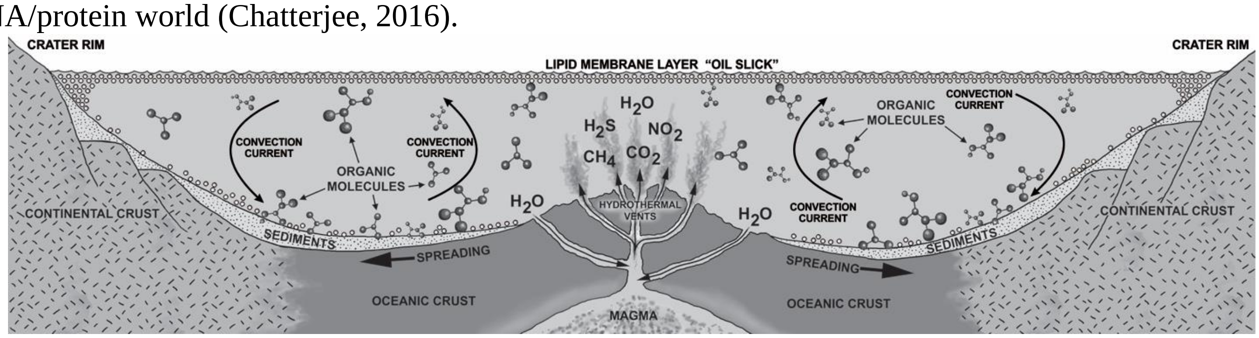

Figure 1. The crucible of life. During the Early Archean period (~4 Ga), freshwater crater basins with hydrothermal vent system at their central peak, would have offered a protective sanctuary for the origin of life. The boiling water was rich with organic molecules brought by meteorites. On the water's surface, primitive lipid membranes and hydrocarbons float like an oil slick. The minerals along the floor of the basin acted as a catalytic surface for the concentration and polymerization of monomers. The bubbling, biotic soup was thoroughly mixed by convection currents. These same currents also circulated some of the lipid membranes down to the basin floor where they attached to the porous mineral layers, encapsulating biopolymers such as RNA and amino acids. Heat, gases, and chemical energy such as ATP released from the hydrothermal vent brewed and condensed the prebiotic soup, which began to collect at the mineral substrate, at the bottom of the basin (after Chatterjee, 2016).

A network of craters, both small and large, has the optimal possibility for processing life synthesis, because a smaller crater has the advantage of a rapid concentration of building block molecules, but a larger crater with its large vent has a higher energy input for chemosynthesis and can retain hydrothermal activity for more than million years. The closely spaced crater basins were interconnected through an extensive underground network of tunnels and cracks that interlinked closely-spaced craters. Cosmic ingredients and temperature gradients could move from one crater to another through these elaborate underground networks thus increasing the chances for the right crucibles to form life (Fig. 2). These crater-lakes were separated and isolated by raised rims on the surface, but were interlinked through underground cracks and crevices. These networks connected craters, ranging in size from 5 km to 500 km diameter, had a higher probability of forming the ideal crucible systems for the origin of life than a single crater. The bootstrapping a network of crater-lakes becomes increasingly suited to facilitate the prebiotic synthesis enhancing the condition for biosynthesis. This network of impact-crater-lakes invokes a system something like the Mono Lake in California, where a series of lakes from higher to lower elevation have a linked flow of groundwater.

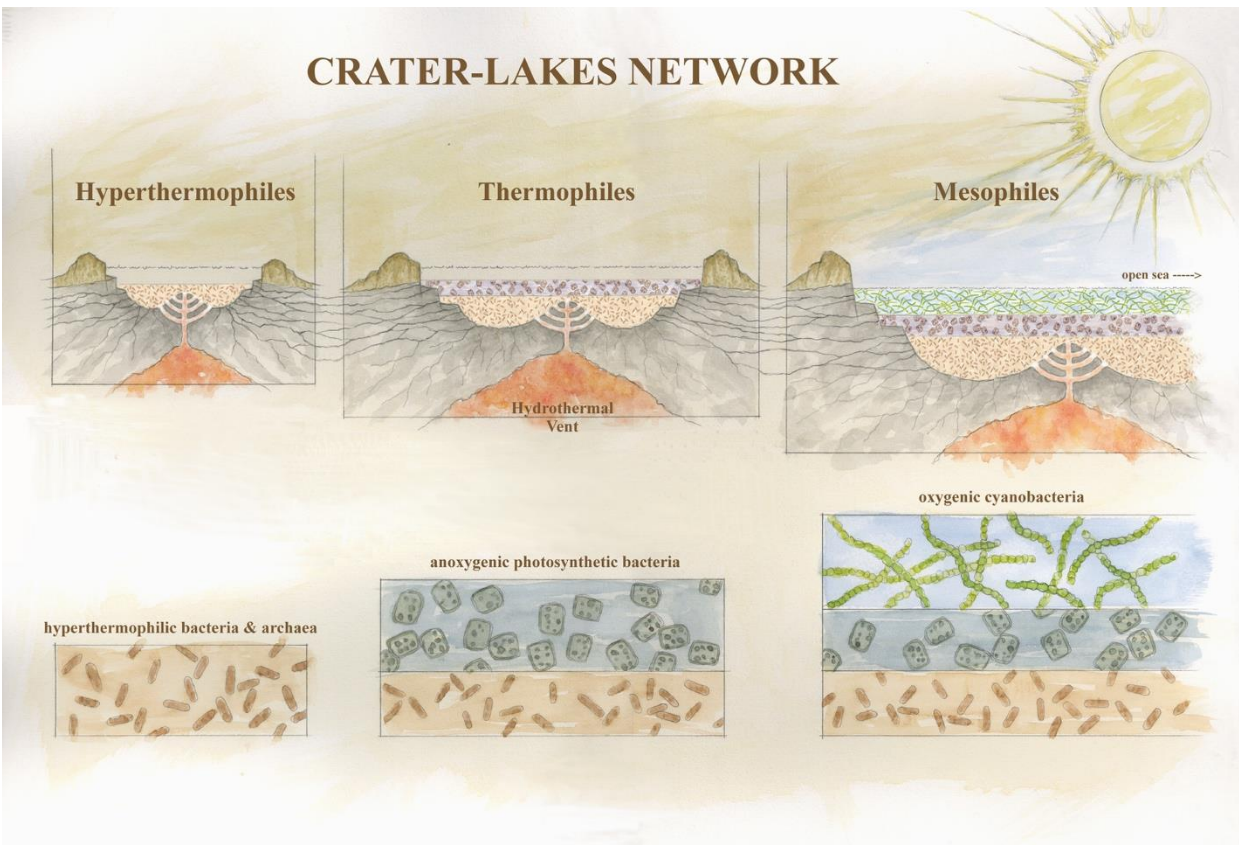

Figure 2. Along the top of the illustration, three cross-sections of crater-lakes of different sizes show 1) the underground fissure networks that connect the closely-spaced crater basins, and 2) the vertical gradients of microbial communities. Within these percolating crater-lakes three microbial zones form. The first hyperthermophilic zone, along the bottom of the crater-lake, is where bacteria and archaea first emerge. Above that, the thermophilic zone forms, and in that layer, anoxygenic photosynthetic bacteria evolve. Within the top mesophilic zone, as the crater-lake merges with the ocean, oxygenic cyanobacteria evolve, and begin to photosynthetically harness the Sun's energy – Earth's first oxygen is the by-product. Along the bottom of the illustration, those three microbial zones are enlarged (after Chatterjee, in press).

Impact crater-lakes on Mars

Earth is the only habitable world we know thus far but the raw ingredients required for life appear everywhere, from the asteroids to the interstellar gas clouds in the Solar System. Our planet's life-giving hydrothermal crater-lakes could be used as analogs on the search for life in other planets. Mars was once clearly very Earth-like during Noachian (~4 Ga) and enjoyed a warmer climate, when water flowed freely across its surface, carving rivers, accumulating in crater-lakes and oceans. There are about 180 impact crater-lakes on Mars at Viking Resolution. The habitats for microorganisms in hydrothermal impact crater-lakes on Earth could be useful in search for life on Mars (Farmer, 2000). Curiosity rover has found an active, underground and variable source of methane, a possible source of life today. Building on the recent NASA exploration of Martian life, the hydrothermal crater-lake of early Earth is the terrestrial equivalent of the habitable environment of the Gale crater of Mars, which is characterized by neutral pH, low salinity, and variable redox states of both iron and sulfur compounds (Grotzinger et al. 2014). The long-term habitat stability and the wide distribution of the hydrothermal crater basin has major implications for understanding the evolution of microbial life on other planets.

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NATIONAL ACADEMIES CALL FOR WHITE PAPERS ON ASTROBIOLOGY SCIENCE STRATEGIES FOR THE SEARCH FOR LIFE IN THE UNIVERSE

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SECTION I: ADMINISTRATIVE INFORMATION

A. Cover Sheet

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(2) White Paper Title: Searching for (Proto)Cellular Logics Proteins in Earth-like Environments Hospitable and Inhospitable to Life

(a) White Paper Running Head: Searching for (Proto)Cellular Logics Proteins in Earth-like Environments

(3) Relevant Topics of the NASA Astrobiology Strategy 2015: Synthesis and function of macromolecules in the origin of life, Early life and increasing complexity, Co-evolution of life and the physical environment

SECTION II: WHITE PAPER

A. Executive Summary

Ca^{2+}-dependent cellular intelligence, decision making, or logics represent a major ubiquitous and diverse form of adaptive response regulation mediated by sets of single and/or multiple component intracellular systems often conserved across and within taxonomic classifications of life on Earth [cf. 1-6]. Such systems contribute to expression of a wide variety of important life-sustaining phenomena at the cellular level, including, but not limited to, bioenergetics, posttranslational protein and lipid modification and transport, homeostasis, motility and fate, proliferation, extreme environment adaptation and transformation, and complex social-like behaviors [7-27]. Given its pivotal role in the origin and evolution of extant viruses/phage, Archaea, bacteria, fungi and molds, protozoa, and metazoa, Ca^{2+}-dependent cellular logics systems and their constituent macromolecules, biochemical pathways, and organelles offer unmatched opportunities for better understanding fundamental aspects of fitness and selection on Earth and for possibly finding evidence of macromolecular synthesis and function in the origins of life, of early life and increasing complexity, and of coevolution of life and the physical environment elsewhere in the universe. However, despite these promising distinct advantages for astrobiologycal sciences and discovery, basic scientific knowledge and technical approaches for valid, robust, and sensitive life detection need further advancement before significant breakthroughs may be achieved for solar and extrasolar system exploration.

B. Background and Innovation Claims

Being influential, exquisitely adapting elementary organisms on Earth, it is unsurprising that microbes serve as relevant scientific models for possible solar and extrasolar system life. All microbes, from viruses to protozoa, make decisions throughout their lifespan [2,3,7-27]. They sense, interpret, and even manipulate changing internal homeostatic states and/or local ambient and host environments, often staying with the same strategy or switching between alternative strategies of differential fitness to determine, for instance, vegetative and reproductive cycles, phenotype, motility, stress resistance, stages of infection, and social cell-cell interactions. Successful strategies can increase a microbe's viability and/or fecundity and may vary with inherited life-history traits, random or directed mutations and epigenetic modifications, and traditional forms of dual-process nonasscoiative and associative learning and memory. Strategy acquisition, storage, modification, selection, and execution by microbes frequently require the coordination of Ca^{2+}-dependent sensory transduction pathways, gene regulatory networks, membrane and intracellular transport systems, metabolism, and motility and adhesion apparati, making microbes highly complex computational agents crucial to understanding the origins and evolution of life on Earth and throughout the universe.

Cellular intelligence, decision making, or logics. Recognizing the dynamic goal-directed computational nature of microbe behavior and physiology, modern virologists, bacteriologists, phycologists, and protistologists now revisit the idea, first more-or-less anecdotally reported by early twentieth-century scientists, that both solitary and colonial microbes exhibit degrees of intelligence [2,8,18,19,21-23,26]. The kinds of nonsocial and social intelligences evolved in microbes might not attain that observed for phylogenetically more recent eukaryotic organisms. Nevertheless, the controversial idea of self-deterministic microbial behavior has profound scientific and technological implications. For example, the ability of microbes to solve ecological dilemmas within a single generation or over many generations has been found to play significant roles in many contexts that affect the life and evolutionary trajectories of individual microbes, their communities, and environments, such as host-parasite and parasite-parasite interactions, mate selection: foraging, hunting, and farming: collective defenses against predators and stresssors, kin recognition, quorum sensing, and social altruism and cheating [2,3,7-27].

Ca^{2+}-mediated macromolecular logics in early life complexity and coevolution. Ca^{2+}-mediated macromolecular logics systems underlying many of the above noted cellular response regulation phenomena [1,4-6,28] arise from modular or superfamily protein structural domains that serve as evolutionary units whose members share a common evolutionary ancestor and render, via genetic duplication and recombination, functionally diverse protein repertoires encoded in genomes (see Figure 1). Superfamilies

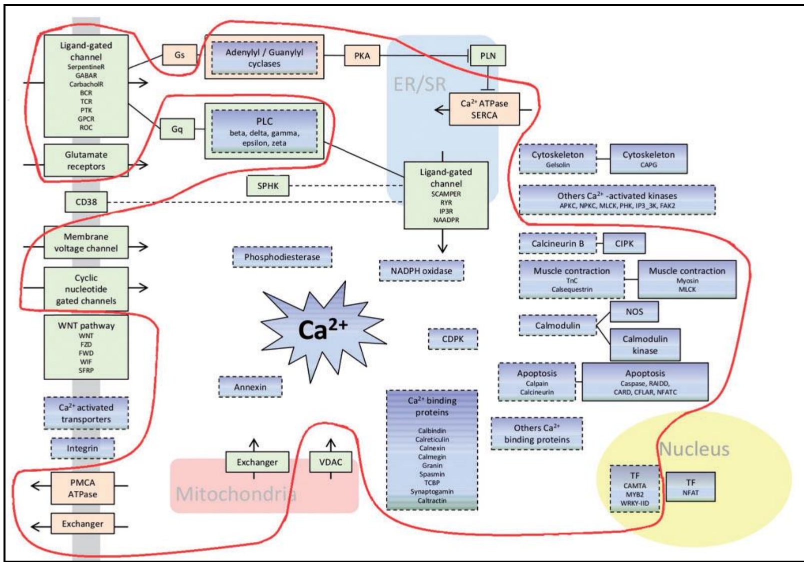

Figure 1. Intracellular Ca^{2+} signaling domain components. Dash-lined boxes depict Ca^{2+}-binding components; green boxes depict Ca^{2+}- influx components; pink boxes depict Ca^{2+}-efflux components; blue boxes depict signal decoding and relay components. Components comprise minimal toolkit for organisms expressing at least one molecular domain architectture function. Figure adapted from [28].

show some nonuniform or heterogeneous distribution across simple prokaryote to complex eukaryote species, with greater abundance and diversity usually positively correlated with genome size, recombination, and evolution [28]. Compared to other taxa, Ca^{2+}-signaling toolkits of eukaryotes have experienced much more expansion and diversification, coinciding with organismal complexity and cell-type differentiation. But, the toolkit is evolving toward increased abundance and diversity of integrated, single-purpose proteins, rather than multipurpose Ca^{2+}-binding macromolecules shared with ancestors [28] – a trait that arguably improves the decision-tree and affector-effector capabilities of cellular logics systems in more complex organisms. *Thus*, Ca^{2+}-signaling toolkits and the genes that encode and regulate them provide unique dissociating biosignatures to molecular fingerprint life origins, evolution, and complexities associated with large highly diverse phylogenetic trees.

Coevolution enabled viruses to coopt these more sophisticated host intracellular Ca^{2+}-signaling pathways to optimize timing and effectiveness of infection stages against barriers to invasion, pathogenesis, replication, and release [2,3]. Virus-induced changes in free cytosolic Ca^{2+} levels facilitate virus adsorption, uncoating, catalysis, toxin production, structural assembly and stabilization, trafficking, and fusion and budding (see Figure 2). Ca^{2+}-associated alterations in virus status also selectively precipitate host cyto-

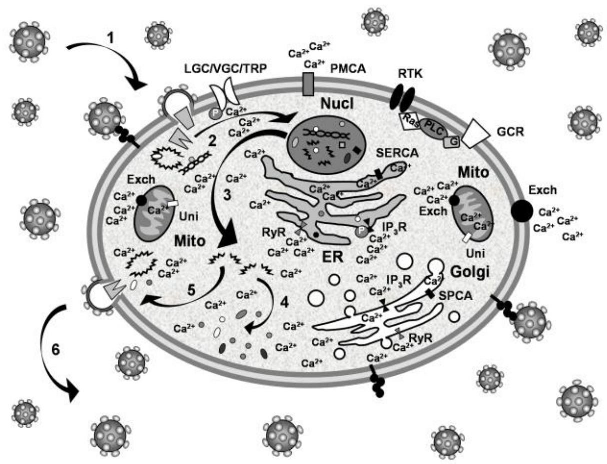

Figure 2. Virus attacks on eukaryotic host Ca^{2+} systems to optimize infection stages. Infection of host proceeds with normal virus lifecycle, here an arbitrary lentivirus-type lifecycle. (1) Mature virus particle docks with host cell via the high-affinity binding of phospholipid-envelope glycoproteins to host surface recaptor. Surface receptor retracts and tows particle to lipid-bilayer cell membrane. Virion fuses to and breakdown cell membrane, injecting capsid into host cell cytoplasm. Envelope and capsid proteins activate inward conductance of host ligand- (LGC) and voltage-gated (VGC) Ca^{2+} channels to promote virus docking, capsid release and uncoating, replication, pathogenesis, and enzyme activity. Similar compounds also increase pathogenicity by indirectly stimulating inositol 1,4,5-trisphosphate receptor (IP_3R) Ca^{2+} conductance from intracellular stores. (2) Reverse transcription of positive single-stranded viral RNA begins and completes synthesis of viral DNA. Double-stranded viral DNA migrates to host cell nucleus (Nucl), where viral integrase enzymes incorporate viral genes into host genome. New viral mRNA molecules are transcribed and spliced. (3) mRNA enter host cytoplasm from nucleus, where (4) they are translated into proteins. Viral regulatory proteins may further activate LGCs, VGCs, and IP_3Rs to elevate intracellular free Ca^{2+} concentration. Higher free Ca^{2+} levels facilitate (5) assembly and budding of immature virion and effects eventual apoptosis via endoplasmic reticulum (ER) and mitochondria (Mito) Ca^{2+} interface. (6) Newly formed virus particle enters host extracellular matrix. Figure adapted from [3].

pathologies through, among other events, retardation or induction of apoptosis, elevation of metabolic stress and reactive oxygen species production, and promotion of proinflammatory cytokine and chemokine synthesis and release. Viral particles and proteins tune spatiotemporal dynamics of host free cytosolic Ca^{2+} concentrations by modulating Ca^{2+} entry from the extracellular environment, upstream first or second messengers, ion- and ATP-dependent Ca^{2+} pumps that sequester or extrude free cytosolic Ca^{2+}, store-operated Ca^{2+} mobilization and leakage, and viral capsid/envelope and downstream host Ca^{2+} binding proteins and sensors.

Exploitation of host Ca^{2+}-signaling systems is a mechanism of survival and reproduction also coevolved by *Clamydia pneumoniae*, *Legionella pneumophila*, *Mycobacterium tuberculosis*, *Leishmania spp*, *Trypanosoma cruzi*, *Entamoeba histolytica*, *Enterococcus faecalis*, and other pathogens [2,29]. Normally bacteria evade host defenses by, for instance, usurping membrane repair systems, downregulating redox immunological responses, and mimicking proinflammatory chemokine and cytokine mobilization of hosts.

Such pathogens facilitate influx of Ca^{2+} into macrophages during the invasion phase of infection, thereby increasing the activity of reactive nitrogen and oxygen response pathways as well as diminishing the apoptotic effects of elevated intracellular Ca^{2+} concentrations for the host cell. Protozoan pathogens and parasites similarly prime the host environment through toxin-activated Ca^{2+} influx into host cells and additional mechanisms.

C. Challenges for Technical Approaches

Framed by the limited, but illustrative, context of infectious diseases, the above exemplars underscore ecological and evolutionary significances of Ca^{2+}-mediated macromolecular logics systems for early life complexity and coevolution on Earth. Such systems govern cellular decision making in solitary and social-like scenarios and therefore exert powerful control over a broad range of functions valuable to the survival and proliferation of viruses/phage, Archaea, bacteria, fungi, protozoa, and metazoa [1-29]. In controlling host systems, infective agents, for instance, secure their own existence while regulating host physical status and ecological niche dominance. Although eukaryotic Ca^{2+}-dependent response regulation has been well studied for decades, much remains unknown about the structure and function of such systems in comparatively primitive life forms (e.g., phage-bacteria symbioses) and how they may alter ambient and targeted host environments. Nonetheless, promising emerging laboratory findings from prokaryotes and eukaryotes suggest strong genomic and proteomic trends for intracellular Ca^{2+}-signaling systems can be employed as dissociable biosignatures of selected life complexity and coevolution. Concerted scientific efforts over ensuing years thus need to better characterize Ca^{2+}-binding protein superfamily structure-function relationships for Earth organisms, such as those involving single and multiple purpose proteins, to predict and profile potential life elsewhere in the universe. Future research should also systematically determine distributions of thermodynamic stability and degradation byproducts for *in situ* and *ex vivo* protein superfamilies, in order to establish molecule function and detection boundary conditions over hospitable to inhospitable Earth-like environments. Macromolecule stability and degradation descriptions will improve biosignature detection probabilities with state-of-art remote instruments and will assist in development and deployment of higher performing next-generation detection instruments.

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The Role of Laboratory Data to Interpret Results from Europa Clipper: Mission Success, Habitability and Landing Site Characterization

by

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Astrobiology Science Strategy for the Search for Life in the Universe
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Introduction

Europa Clipper currently has multiple instruments for remotely mapping composition and geology of Europa. One of the main goals is “NASA's Europa Clipper will conduct detailed reconnaissance of Jupiter's moon Europa and investigate whether the icy moon could harbor conditions suitable for life.”

Here we argue that a major limiting factor for the scientific success of the Clipper mission will be our ability to adequately and accurate interpret the remote sensing data collected by the available instruments. Importantly, the solution to this problem does not require any modifications to the spacecraft or mission as a whole, but rather it requires a dedicated, well-coordinated, and systematic approach to laboratory investigations that are needed to interpret the Clipper data.

Such an investment and effort will yield scientific returns not just for Clipper, but also for existing Cassini data and for all ice-covered ocean worlds that are currently of interest to NASA’s solar system exploration program. ***With a relatively small, dedicated investment NASA could significantly improve the science return of past, present, and future missions.***

The following quotes are from: https://www.jpl.nasa.gov/missions/europa-clipper/

“NASA has selected nine science instruments for the mission. The selected payload includes cameras and spectrometers to produce high-resolution images of Europa's surface and determine its composition. An ice penetrating radar will determine the thickness of the moon's icy shell and search for subsurface lakes similar to those beneath Antarctica's ice sheet. The mission will also carry a magnetometer to measure the strength and direction of the moon's magnetic field, which will allow scientists to determine the depth and salinity of its ocean. Gravity measurements will also help confirm the existence of Europa's subsurface ocean. “

“A thermal instrument will survey Europa's frozen surface in search of recent eruptions of warmer water at or near the surface, while additional instruments will search for evidence of water and tiny particles in the moon's thin atmosphere. NASA's Hubble Space Telescope observed water vapor above the south polar region of Europa in 2012, providing potential evidence of water plumes. If the plumes' existence is confirmed -- and they're linked to a subsurface ocean -- studying their composition will help scientists investigate the chemical makeup of Europa's potentially habitable environment while minimizing the need to drill through layers of ice.?”

“During the nominal mission, the spacecraft will perform 45 flybys of Europa at closest-approach altitudes varying from 1700 miles to 16 miles (2700 kilometers to 25 kilometers) above the surface.”

If NASA also sends a lander after Europa Clipper is launched, a critical task for Clipper will be to search for landing sites where landing can be safe, and where the lander might find the chemicals indicative of the mission goals, including habitability and the ultimate: evidence for past or present life. The requirement of Europa Clipper to find such locations is an additional requirement levied after the current instrument suite were proposed and selected. ***This critical component of the Europa Clipper mission means that detections of the chemical signatures and habitability plus landing site assessment must be completed quickly during the mission and not left for future generations. The assessment must be completed for the success of the lander mission. We stress that the lab work is needed for the success of the Clipper mission independent of a lander mission. The lander mission only makes the situation dire.***

Europa Clipper instruments

The Europa Clipper instruments are:

Optical Remote sensing:
- Ultraviolet Spectrograph/Europa (UVS) 55-210 nm (0.055 to 0.21 micron), $\lambda/\Delta\lambda$ ~220.
- Europa Imaging System (EIS) as 6 broadband filters from ~300 to 1050 nm (0.2 to 1.05 micron).
- Mapping Imaging Spectrometer for Europa (MISE) covers 0.8 to 5 microns at 10 nm/channel.
- Europa THermal Emission Imaging System (E-THEMIS) 7-14, 14-28, and 28-70 micron bands.

In Situ Composition Sensing:
- MAss SPectrometer for Planetary EXploration/Europa (MASPEX)
- SUrface Dust mass Analyzer (SUDA)

Other Sounding:
- Plasma Instrument for Magnetic Sounding (PIMS)
- Interior Characterization of Europa using MAGnetometry (ICEMAG)
- Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)

Background

We will only discuss in this document, readiness for the chemical composition and geologic mapping of Europa leading to detection of the scientifically interesting chemical compounds and intelligent decisions as to where to put down the lander. Other instruments may/may not have data interpretation issues but will not be discussed here. The optical remote sensing instruments that resolve Europa's surface in great detail are: UVS, EIS, MISE, and E-THEMIS. Together these instruments cover the UV to thermal IR wavelength range in varying degrees of spectral sampling and spatial resolution. The E-THEMIS thermal IR instrument only has a few spectral channels and is optimized for imaging at thermal wavelengths and not designed for detailed composition, mainly senses temperature and will not be discussed further.

UVS covers the range 55-210 nm with good resolving power while EIS currently has only 6 broadband filters from ~300 to 1050 nm. MISE covers 0.8 to 5 microns at 10 nm/channel. On paper, it looks like good spectral coverage: 0.055 to 5 microns—the range of solar reflected light. But the spectral gaps and regions of low spectral resolution make data interpretations more difficult and will be discussed below.

The Spectra of the Galilean satellites in the 0.2 to 5 micron reflected solar range are shown in Figure 1. The spectra in Figure 1 illustrate some limitations in our understanding of the spectral features. Note the question marks on the various plots. Another uncertainty is what is the composition of the hydrate(s) in the Europa spectrum? Is the hydrate composed of salts, acids, mixtures, or something else—that has been a long term question with much debate for about two decades. There are reasons for the uncertainties: 1) insufficient laboratory reference data, 2) laboratory studies that did not include the wavelength range of the Galileo and Earth-based telescopic data, and 3) insufficient signal-to-noise ratio (S/N) and spectral resolution in the spectra of the Galilean satellites. At wavelengths beyond 1 micron, water absorptions dominate the spectral structure of the Europa spectrum. The water on the leading side of Europa is ordinary water ice, but on the trailing side the water absorptions are shifted, indicative of different hydrogen bonding. Is the water in minerals such as salts, or acids, and what is the role of radiation? Intense scientific debates over the years have not resolved the problem, in large part due to insufficient laboratory studies. MISE will deliver the data, but how well can that data be interpreted without relevant laboratory observations?

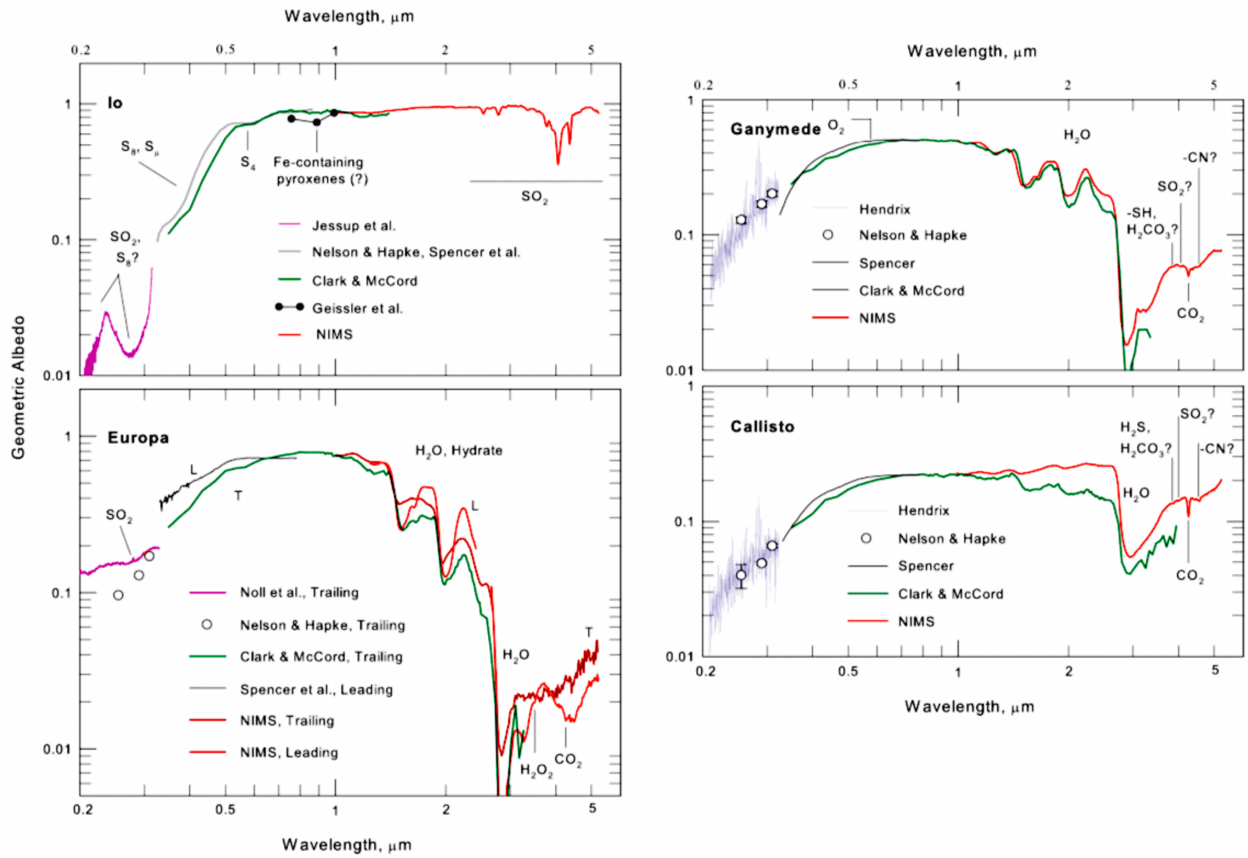

Figure 1. Spectra of the Galilean satellites over the spectral range covered by Europa Clipper instruments (except for the deep UV). From Clark et al., 2014.

At wavelengths between 0.2 and about 1 micron, water ice is very transparent and Europa's UV to visible spectrum shows a non-ice absorber that reddens and darkens the trailing hemisphere to about 1 micron and the leading hemisphere to about 0.5 micron. Most icy objects in the Solar System show a yellow/red spectrum indicative of a non-ice component although in general, the UV absorber has yet to be identified. Note in Figure 1 that there is a weak absorption between 0.2 and 0.3 micron, and there is small feature near 0.6 micron on Europa that has been tentatively identified as sulfur. A similar UV absorption is seen in Saturn's satellites possibly suggesting a wider solar system process (Figure 2).

Despite a 13 year orbital tour of the Saturn system with the Cassini mission, we still do not have a definitive answer as to what the UV absorber is in the ice. Leading candidates are tholins and space-weathered meteoric dust with hydrated nano-phase iron oxides. Is there a connection between the UV absorber between 0.2 and 0.3 micron on Saturn's satellites and Europa? What is the absorption due to? We do not know. Several candidates have been proposed by different authors. Cassini did not cover this UV spectral range with a spectrometer capable of resolving the feature, and only a few broadband channels in the imaging instrument showed the general trend in the spectrum. Europa Clipper has similar limited spectral capability.

The satellites in the Saturn system display classic ice absorptions (except Titan which is shrouded in a smoggy methane atmosphere). The ice in the Saturn system shows excellent crystalline ice spectral features, mixed with varying amounts of non-ice with the UV absorber. In this sense the Saturn system is relatively simple compared to the Jupiter system and Europa whose surface ice is heavily radiation damaged. The Saturn system is a weak radiation environment compared to Europa and the Jupiter system.

The Jovian system, particularly Europa, is entirely different from any Saturnian icy body, for the reason that very-high-energy radiation (eletrons, protons, and heavier ions at MeV energies) that penetrates far deeper (up to several tens of centimeters) than the skin depth of the optical spectrometers on board Europa Clipper. The question that needs to be addressed is: does the top few millimeter surface characterized by these spectrometers represent a good approximation for the chemical composition of tens of centimeters below the surface? In order to address this question, laboratory work needs to be conducted with realistic energies representing Europa's surface environment.

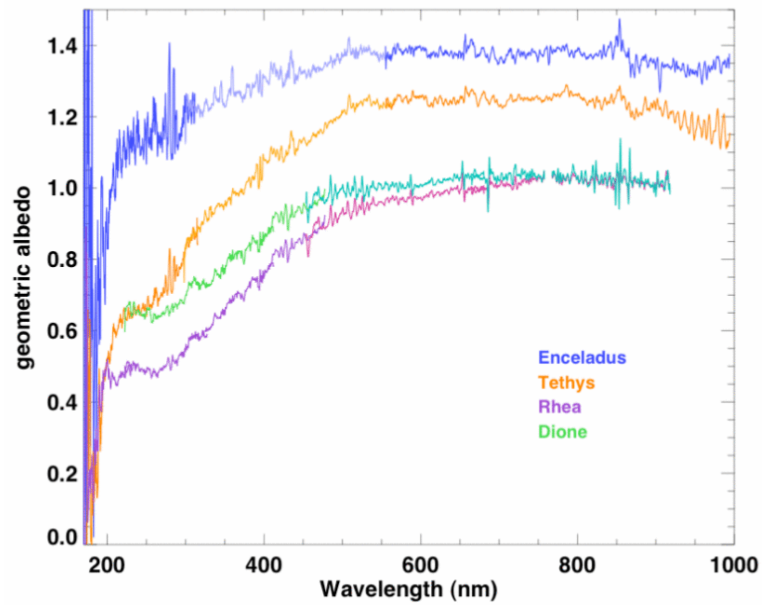

Figure 2. UV spectra of Saturn's satellites, from Noll (2008).

Are We Ready to Interpret Clipper Data?

There remain many unidentified spectral features in spectra of the surfaces of the Jovian and Saturnian icy satellites. We still have not definitively identified the UV absorber in the surfaces of Saturn's inner satellites and rings, despite a 13-year mission. Why do these identifications remain uncertain? **It is mainly due to the lack of laboratory data obtained for relevant materials, at relevant wavelengths, under conditions appropriate to the surfaces of icy satellites (including temperature and radiation).** Also, a with lack of spectroscopic imaging to map the locations of the 0.2-0.3 micron feature, and potentially finding higher abundance outcrops, we have no idea of its potential geologic origin. Identification of the dark material on Iapetus is more definitive (Clark et al., 2012), largely due to Cassini VIMS resolving the dark material spatially (Figure 3), combined with a unique 3-micron absorber that is only seen in nano-phase iron oxide. But it took 8 years to find that solution (2004 to 2012) and the specific iron oxide has yet to be determined (hydrated Fe_2O_3 – Fe_3O_4 match; do other iron oxides?).

A lack of appropriate laboratory data continues to limit the identifications of the compositions of the surfaces of icy satellites. Between the Galileo mission to the end of the Cassini mission in September 2017, we have certainly learned a lot from laboratory studies and modeling. We have considerably more laboratory data, better radiative transfer models, more optical constants and better software tools. But is this enough for the Europa mission? No.

We still have few optical constants of materials, including those relevant to icy bodies, and NONE for the temperatures found on Europa over the entire Europa Clipper wavelength range (~0.1 to 5 microns). Only a single material comes close: H_2O ice. The Mastrapa et al. (2008) optical constants for crystalline and amorphous ice are the best available, and while they cover a broad temperature range, no measurements were made in the visible and UV. Clark et al. (2012) found discrepancies with lab data and made corrections on a single temperature set (120 K) for crystalline ice. Subsequent to the new VIMS RC19 calibration, new comparisons of lab data show that Mastrapa's optical constants need further adjusting in the 1.2 – 2.5 micron range. This is not meant to be a critique of a specific investigator's results, only to indicate the difficulty in measuring optical constants over a large wavelength range and that verification is needed using laboratory reflectance measurements and modeling. Even for H_2O and many other standard ices such as CO_2, the vacuum ultraviolet (VUV) region (0.1 – 0.2 microns) needs reliable optical constants.

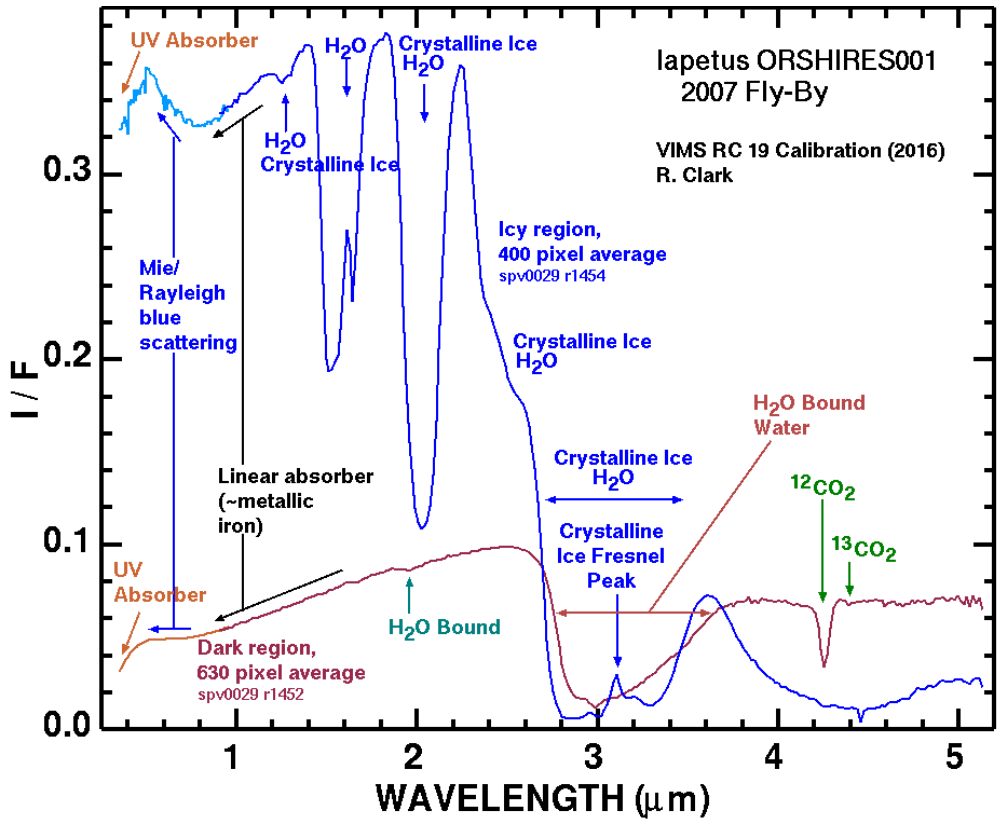

Figure 3. Cassini VIMS spectra of Iapetus. After Clark et al., 2012 but updated with the newest VIMS calibration.

We have no optical constants for crystalline H_2O ice at Europa's temperatures in the visible or UV. There is only one set of UV optical constants for crystalline H_2O ice in the visible-UV but is for terrestrial polar temperatures, far warmer than Europa. We have no idea if the UV absorptions in crystalline ice shift with temperature as do all the IR absorptions. We have NO spectra in the UV of amorphous ice, even in transmission or reflectance, let alone absorption coefficients. ***As a result, the ability to model spectral signatures and determine Europa's surface composition and abundances from Europa Clipper data will be extremely limited.***

A significant controversy with interpreting spectra of the trailing side of Europa is what signatures are due to salts versus acids, and how does radiation damage to such materials change the spectral response? Getting such a simple interpretation correct has huge implications for ocean and habitability. Key factors in this controversy are the limited spectral ranges of laboratory data and the type of radiation used, if any. Through at least the 1990s into the first decade of the 21st century, most lab data on salts only extended to about 2.5 microns and most were obtained at higher temperature (Galileo NIMS went to 5-microns and so does MISE). The best discrimination between salts and acids is by sufficient spectral resolution in the 2 to 5 micron region, which MISE satisfies. Could the UV also be used to discriminate the possibilities? More laboratory spectra of salts and acids are needed from 0.1 to 5 microns. It is also rare for lab data to extend into the UV. As with the ongoing inability to identify the UV absorber in the Saturn system, we have no ability to make any identification of the UV absorber in the Jupiter system. **Again, the lack of laboratory data is the culprit.**

We have a growing spectral library on the infrared that could help MISE detect organic absorptions in the 1-5 micron region (e.g. Kokaly et al., 2017 and references therein). But, without spectral measurements of materials that are candidates for the bulk non-ice materials on Europa, we could have difficulty 1) detecting these compounds in the presence of ice or acids, and 2) we do not have spectra of the radiation products that might be created in the Europan environment.

Example spectra of some organic compounds and minerals are shown in Figures 4 and 5. Note the incredibly rich spectral structure. Some organic compounds, in particular polycyclic aromatic hydrocarbons (PAH) fluoresce when stimulated by UV light as shown by the spectra in Figure 5. These are the wavelengths were ice is very transparent, and these wavelengths would allow the highest sensitivity of detecting such compounds on Europa. While Clipper covers this wavelength range, it does so only with broad filters in the EIS instrument, which as Figure 6 demonstrates will be insufficient for the detection of organics implying the MISE and UVS instruments will be the prime instruments for detecting organics on the surface. Note that the radiation environment at Europa might induce fluorescence in compounds, but we have little laboratory data to interpret such a signal. Fluorescence could be at any wavelength from UV to IR, and again, measurements are needed at relevant temperatures.

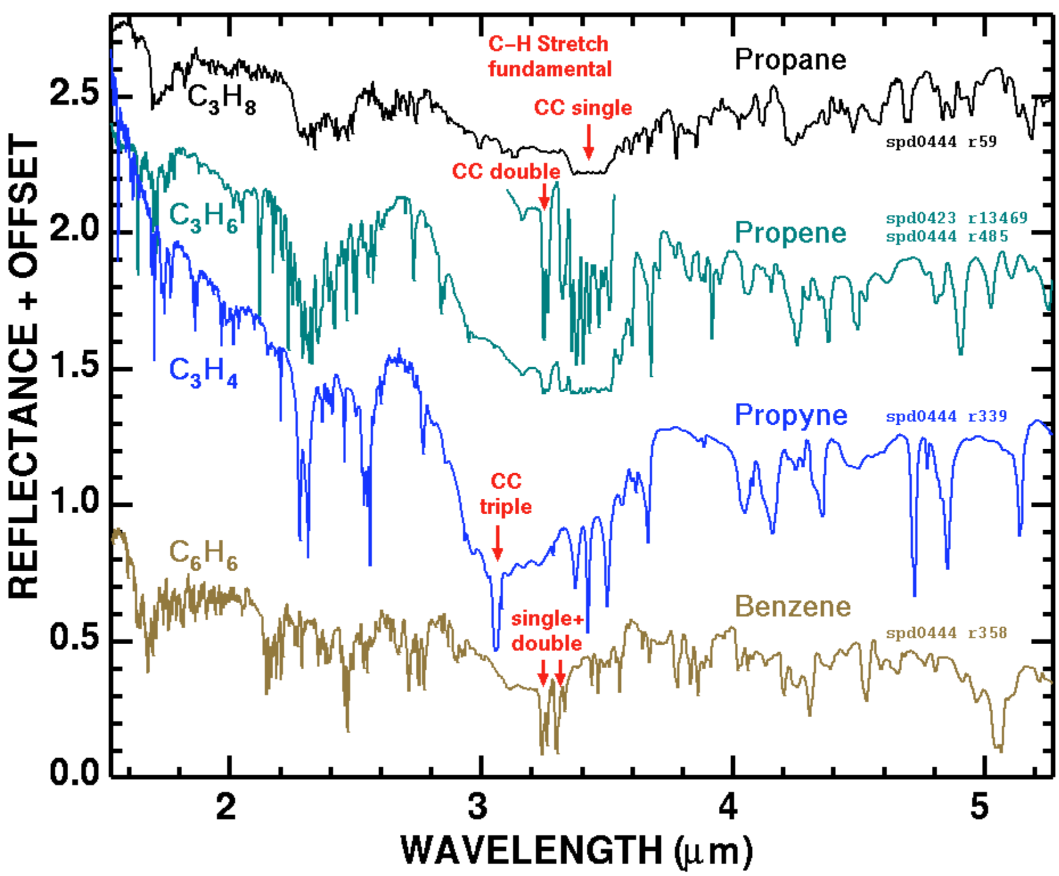

Figure 4. Example spectra of organic compounds with varying bonds over the MISE spectral range. H_2O ice, salts, and acids are more transparent in the visible and into the near UV. From Clark et al., 2008.

In H_2O ice, a strong absorption occurs at wavelengths shorter than 0.18 micron. Detection of trace organics H_2O ice is possible with abundance limits changing with wavelength. Detection of compounds short of 0.18 micron in H_2O ice is at least as difficult as in the 3+ micron region. But ice is very transparent between about 0.19 and 0.8 micron. That is the wavelength region were other compounds can be detected at extremely low abundances, and this is the reason why the UV absorber in low abundance can color the ice in the Jupiter system, the Saturn system, and throughout the Solar System.

Needed Community Laboratory Facilities

Yes, NASA has funded lab work, but there are questions about much of its relevance to the Europa Clipper mission, largely because NASA has not ensured that laboratories have the needed equipment.

Few laboratories are equipped to measure the reflected solar range of Europa clipper. For example, researchers at a laboratory may have an FTIR and do radiation experiments on ice mixtures producing new products, with results measured in thin film transmission spectra in the 4-20 micron range. But the absorptions measured by Europa Clipper are not covered, including into the UV. Another lab may measure 0.35 to 2.5 microns, but do not include the 2.5-5 micron region or UV. All these incomplete spectra feed a research community making different interpretations of planetary spectra because the same fundamental data are not covered for all instruments on the spacecraft. Consequently, it is difficult for labs to cross-compare and validate spectra of various materials that could be utilized by the broader community. **Much of our Europa and ocean worlds spectroscopic facilities are 'boutique' labs with highly specific and unique capabilities, which is useful, but with a bit more investment NASA could ensure that these labs have the measurement and laboratory capabilities to generate data that is validated and usable by the Clipper team and the broader planetary science community.**

It is important for researchers and managers to understand that experiments need to be conducted over the wavelength range of the Clipper instrument suite and temperature range of the Europan surface to obtain the most precise interpretation of surface composition. This has become clearer over the last decade with the Cassini mission and as shown by recent lab spectra. For example, organic compounds display rich absorption bands in the near infrared (e.g. Figure 4). But when in small abundance in a surface with abundant water present, the strongly absorbing water, whether as ice, adsorbed in minerals, in salts, or acids make it difficult to detect the organics at the lowest levels. MISE will attempt to make such detections through high signal-to-noise measurements. If organics outcrop in higher abundance, MISE could potentially detect them. But organics can potentially be better detected in the near UV where ice is transparent. Thus, UV instruments may be able to detect organics at lower levels, but we need laboratory data to understand the signatures and abundances. Europa Clipper, however, is hampered by the near UV spectral gap. This makes the job of MISE all the more important. In either case, laboratory data on the spectral signatures of trace organics in ice, salts and acids is sorely lacking, and none that we know of covering the deep UV to 5 micron range of the Europa clipper mission.

Note that the radiation environment at Europa might induce fluorescence in other compounds, but we have little laboratory data to interpret such a signal. Fluorescence could be at any wavelength from UV to IR. Example fluorescence signatures is shown in in Figure 5.

We have reviewed the state of laboratory data and its information content to interpret Europa Clipper data and found it lacking. In the following section we discuss solutions.

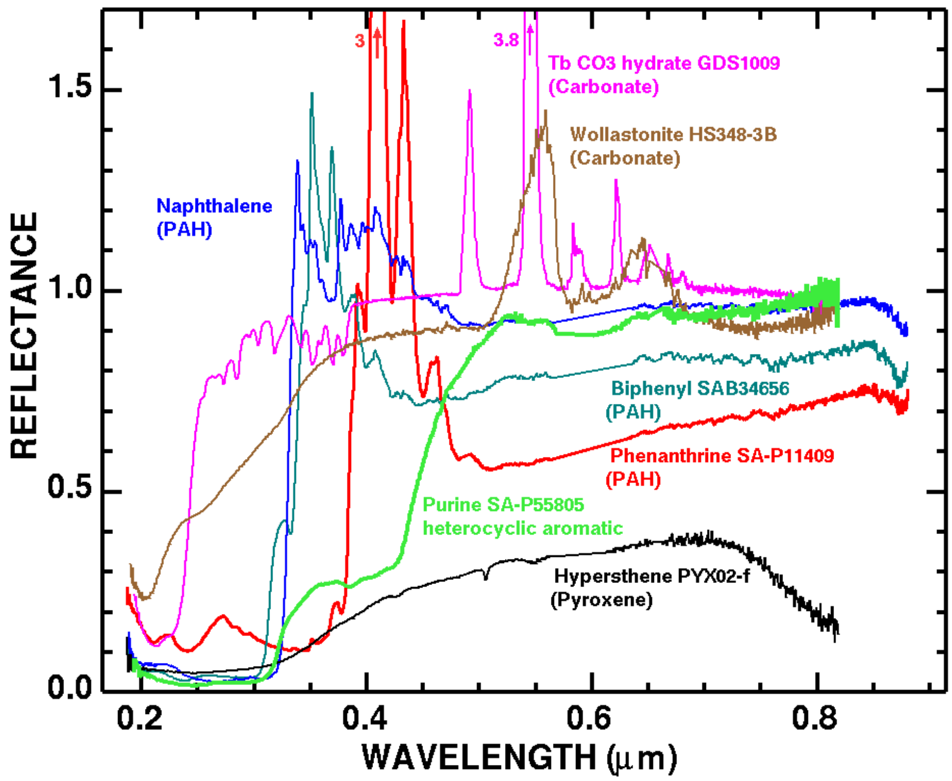

Figure 5. UV-Visible wavelength spectral of some organic and other compounds. The sharp upward spikes are fluorescence emission lines.

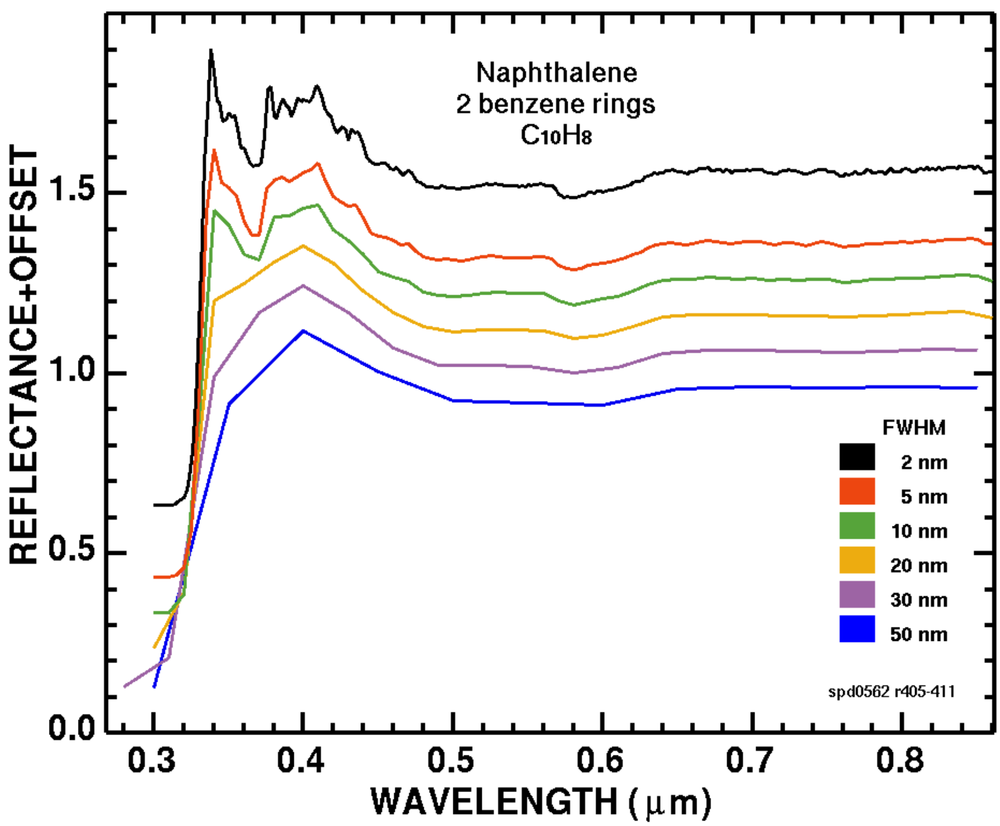

Figure 6, Naphthalene, a PAH, from Figure 5 shown as a function of spectral resolution. At 10 nm FWHM, the emission lines are just resolved, but 5 nm or better is needed to distinguish emissions from other compounds.

Measurements Needed

Laboratories need to measure material relevant to Europa over the entire wavelength range included in the optical remote sensing reflected solar range, 0.1 to 5.1 microns with spectral resolution equal to the instrumentation on Europa Clipper (or adequately resolving the spectral features of Europa chemicals). Minimum would be where ice becomes transparent: 0.18 to 5.1 microns.

Below, temperature means the likely range of temperatures that may be encountered on Europa's surface, from warm ice (up to 270 K) to Polar regions, < 100 K.

1) *Basic needs:*

Confirm Mastrapa's optical constants with reflectance measurements of ice and extend the optical constants as a function of temperature to 0.1 micron. A) Crystalline ice. B) Amorphous ice.

Salts: Spectra from 0.1 to 5.1 microns are needed. Measure the samples as a function of composition and temperature, including at least some optical constants.

Acids: Spectra from 0.1-5.1 microns are needed. Measure as a function of composition and temperature, including at least some optical constants.

SO2: measure 0.1-5.1 microns.

CO2: measure 0.1-5.1 microns.

Organics (Clark et al 2009, 2010; Kokaly et al., 2017) provided a good start to the IR spectral signatures of organics with some cryogenic measurements. But visible and UV measurements are still to be done (data in Figures 5 and 6 begin to address the problem but currently there is no funding to continue that work with the end of Cassini.).

2) *Advanced:*

Mixtures: Measure trace detection of salts, acids, organics in ice and radiation products. Measure from 0.1 to 5.1 microns.

Sulfur and sulfur products implantation into ice: measure 0.1-5.1 microns.

Sodium implantation into ice: measure 0.1-5.1 microns.

Radiation effects on samples. If compounds from the Europan ocean were brought to the surface, how would radiation damage affect those compounds and spectral signatures with exposure age? Knowing such effects is important as a signature that may not be obvious with current data. Knowledge of such signatures may indicate the prime landing location.

While we focused this white paper on the optical remote-sensing instruments, their Europa Clipper Science and the laboratory readiness needs, we think other instruments would be benefited by the laboratory work towards understanding the chemical and geological composition of Europa’s surface. Radiation products and sputtered molecules that might be detected by MASPEX and SUDA need to be included in the laboratory work. Only with such work can we link the detections of the various instruments and therefor make a better assessment of composition and processes.

Laboratory Facilities Needed

Spectrometers covering the 0.1 – 5.1 micron range with cryogenic capability under vacuum with UV and particle radiation capabilities are needed. Measuring wavelengths further into the infrared than 5-microns are also important for sample characterization of radiation products. Mass spectrometry is needed for characterization of evolved products to connect the surface chemistry that might be detected with Europa Clipper optical remote sensing with MASPEX and SUDA.

Currently insufficient NASA funded facilities exists to our knowledge with these capabilities. Simple measurements of a single compound as a function of temperatures take many days to weeks, including measurement of the sample, standards, data reduction and writing up results. The USGS spectral library work, for example, has shown that a single sample measured at room temperature required a person week of work to measure and document. Temperatures series take longer. Thus with the amount of work that needs to be completed before Clipper arrives at Jupiter, many labs need to be funded at full capacity starting immediately.

A number of labs currently exist with partial capability. These are:

JPL (Gudipati, SUDA Co-I): 0.1 – 20 microns spectroscopy, cryogenic systems, 0.1 MeV – 25 MeV electron source (JPL, NIST), large ice-cores (up to 100 cm) at 100 K, laser-ablation mass spectrometry, various VUV irradiation sources.

JPL (Hand, SUDA Co-I). Ocean Worlds Lab (OWL) and Icy Worlds Simulation Facility. The Minos and Rhadamanthys chambers provide visible to Near-IR to Mid-IR reflectance spectroscopy (diffuse and specular geometries) under Europa relevant conditions (10^{-8} torr, 50-180 K). These UHV chambers also provide electron and proton irradiation of cryogenic samples while spectroscopic measurements are being collected. Mass spectrometry via an RGA (1-300 amu) runs parallel with spectroscopic measurements. Samples and mixtures can be either vapor deposited or preloaded onto the cryostat cold finger. Other simulation capabilities in the OWL include bulk ice tests of morphologic changes resulting from diurnal variations in solar irradiance (ARK and Stockpot chambers).

JPL (Dalton, MISE Co-I): The Planetary Ice Characterization Laboratory (PICL). The centerpiece of this facility is the Basic Extraterrestrial Environment Simulation Testbed (BEEST, Figure 7b), a cryogenic vacuum system capable of replicating planetary surface temperatures and pressures, configured to measure infrared reflectance spectra in the same format measured by flight instruments. Capabilities include: vacuum pumps and a chamber cooling to cryogenic temperatures; interfacing multiple spectrometers to enable wavelength coverage from 0.4 to 12 microns; and sample synthesis and characterization capabilities including the formation of hydrated sulfates and organic/ice mixtures.

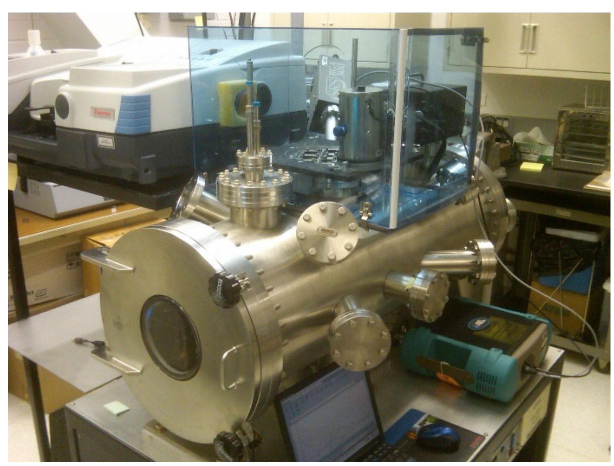

Figure 7b. The BEEST Facility, JPL.

APL (Hibbits, MISE Co-I): 0.14 to 8 micron reflectance spectroscopy, ultra-high vacuum (UHV) environmental chamber with temperatures 100 – 650 K (Figure 7a). While in the chamber, a sample is held in a holder equipped with a dosing line enabling the sample to be exposed to controlled amounts of gases. While in the chamber, samples can be irradiated with 1 – 40 keV electrons up to a fluence of 80 microamps. The samples can also be irradiated with mass selected ions of H^+, O^+, and other gases up to an energy level of 20 keV and a fluence of a few 10s of microamps. The irradiation can be done while the sample is cryogenic or heated. Spectra can be obtained by pausing the irradiation and rotating the sample to the appropriate port for spectral measurement.

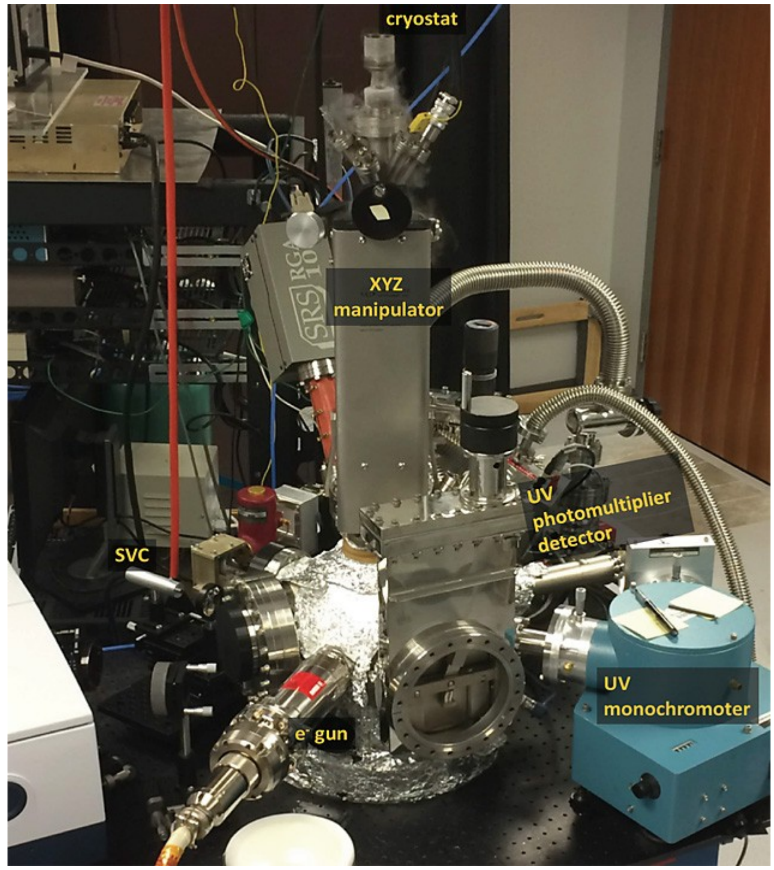

Figure 7a. APL lab facility.

PSI (Clark, MISE Co-I): 0.1-2.5 micron spectroscopy (reflectance/transmittance), vacuum to ~2 bar pressure, cryogenic (LN2) to 495 K, Deuterium Vacuum UV (VUV) light source irradiation (Figure 7c). Reflectance on horizontal samples. The “Brown” chamber can operate 0.18 – 5.1 microns (sapphire windows) and temperatures to 50 Kelvin (current spectrometers go to 2.5 microns) under vacuum. Two additional environment chambers can operate from vacuum to ~2 bars and 77 K to 495 K and measure at various phase angles and reflectance 0.18 – 5.1 microns (sapphire windows) on horizontal samples.

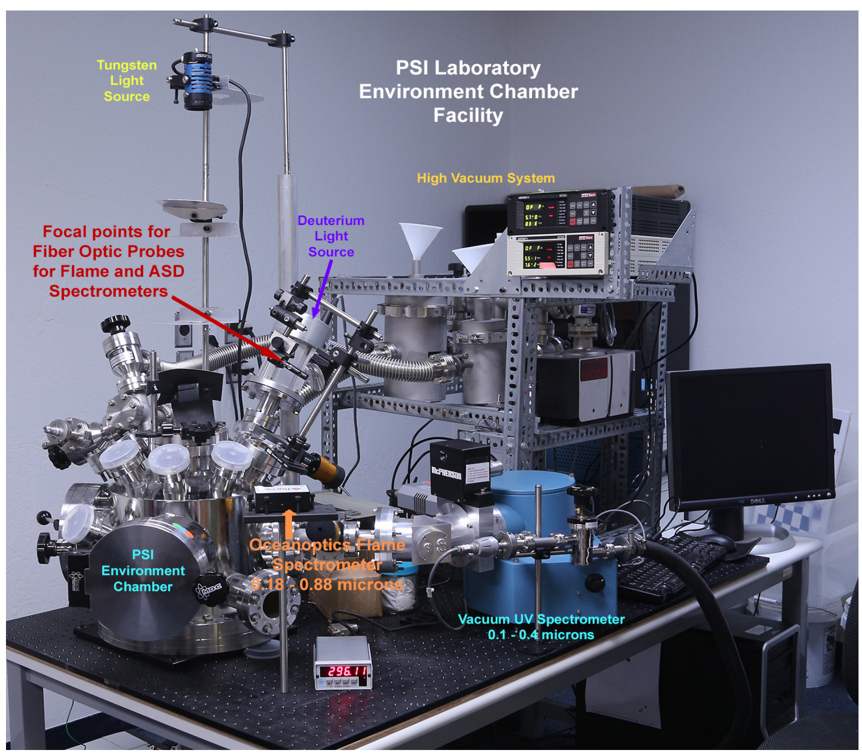

Figure 7c. PSI lab facility large environment chamber.

USGS Denver Spectroscopy Lab (not currently NASA funded): 0.2 – 200 micron spectroscopy (reflectance/transmittance), vacuum to ~2 bar pressure (0.2-5 microns), cryogenic (LN2) to 495 K, UV irradiation. Reflectance on horizontal samples. The USGS lab has produced multiple spectral libraries relevant to the Europa Clipper mission, the most recent, Kokaly et al. (2017a, b).

Recommendations

NASA has funded lab work, but there are questions about much of its relevance to the Europa Clipper mission, largely because NASA has not ensured that laboratories have the needed equipment. Furthermore, a large fraction of the laboratory spectroscopic work that has been funded in the past has focused on Mars, and understanding the surface composition of that world with laboratory spectra collected under conditions relevant to Mars. The Europa Clipper, and the exploration of ocean worlds more broadly, should motivate a significant laboratory effort comparable to that undertaken by the Mars program.

Europa Clipper PI/Co-I labs need to be immediately upgraded and staffed to begin measurements as soon as possible (FY2018). Each lab needs as a minimum one full-time lab tech and a fraction of an FTE (e.g. 0.3) scientist funding. **THIS IS A BARE MINIMUM**. Plus funding to bring each lab up to capabilities of the Clipper mission (0.1 to 5.1 micron spectral range, plus radiation and mass spectrometry). This is only a beginning of the needed fixes to the problem. The scientists involved should meet regularly and coordinate measurement strategies and the work to be accomplished to meet mission needs. After the first year of study, an assessment needs to be done to assess if the funded labs can meet the needs of the mission by the time Europa Clipper enters orbit. If more work needs to be done than can be covered by these labs, either staffing increased and/or the Europa project should look to the broader scientific community to expand capability to meet mission needs before arrival at Jupiter.

Funding sources. It has been suggested that the budgets needed for laboratory work outlined here should have been included in the proposals originally submitted. But detailed budgets were never done and the proposals did not include the response needed to support a lander mission.   Suggestions have also been made to go to the Research and Analysis (R&A) programs for funding. But R&A programs have historically not funded mission work—they say the missions should fund it. The problem we face today of lack of laboratory data is a direct result of the R&A programs not funding lab work. And what if the labs go to the R&A programs and do not get funded? Do the Clipper and Lander missions get delayed? The current success rate of NASA R&A program proposal is very low and it is unlikely they would fund multiple labs for one mission focus.   The system has been broken for decades and it is unrealistic for the R&A programs to fix this problem in the time frame needed, **which is NOW**. The mission project needs to solve the problem, and the labs need to be guaranteed funding much like spacecraft subsystems get funding to assure mission success.

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Life Detection Strategy and the Need for Robust Sample Preparation Techniques

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A major focus of astrobiology is on developing capabilities to enable the search for extraterrestrial life, including investigations to explore where organic synthesis occurs today. As a result, NASA is focusing considerable resources on exploring modern planetary habitats that may have the necessary habitable conditions and sampling these environments for organisms possibly living there now. To conduct measurements that support this science focus, a capable suite of instruments is recommended for development that would employ several techniques and corroborate detections/non-detections, as recommended by the Europa Lander Science Definition Team Report [*Hand et al.,* 2016]. These are difficult measurements to successfully conduct; two notable challenges expected are extremely low biomass abundance and the presence of strong inhibitors to the measurements. Thus, robust sample preparation is needed to enable detections. While any single measurement, on its own, would not provide the confidence necessary for definitive extraterrestrial life detection, multiple indications of life using disparate techniques to find complementary signatures could dispel this ambiguity. We advise here on the value of an analysis that searches for Long Chain Polymers (LCPs), including DNA and RNA, as polymers are known to transfer heritable information down across generations in terrestrial organisms and could act similarly elsewhere. Also, importantly, DNA/RNA detection and sequencing could help rule out terrestrial contamination.

Certain ocean worlds of the outer solar system are believed to harbor conditions conducive to life, including Enceladus and Europa [*Greenberg et al.,* 2000; *Chyba and Phillips,* 2001] and each of these moons likely harbors a global ocean beneath its icy surface. Tidal forcing acts on both moons as they orbit their parent planets and causes frictional heating within the interiors that may provide the energy needed to release heat, sustain liquid oceans and supply chemistry, forming habitable zones. Enceladus, a small icy moon orbiting Saturn, releases ice and dust from its south polar terrain "tiger stripes", a set of fractures. Putative plumes have also been observed at Europa [*Roth et al*., 2014; *Sparks et al.,* 2016]. The plumes and ice shells of Europa and Enceladus present excellent locations to search for life, but occur in challenging environments and are expected to have compositions that will require "biosignature instruments" to decipher measured signals. Challenges include high salinity expected in the ice samples that can ruin downstream analyses, very low biomass, ruling out false positives, low- to micro-gravity, high radiation and lack of atmospheric pressures.

Mars presents intriguing, yet challenging, environments to search for life. Briny liquid water has been proposed to exist near the surface at recurring slope linea (RSL) on Mars [*Ojha et al.*, 2015] or formation by granular flow [*Dundas et al.,* 2017]. At certain locations on Earth, such as the hyper-arid Atacama Desert, microbial communities are supported by the deliquescence of hygroscopic salts, suggesting that if formed by water, RSLs may be locations habitable for life on Mars. Also, water has been shown to exist in other locations on Mars, such as polar caps, ground ice, frosts, hydrated minerals, and even water vapor [summarized in *Dundas et. al.,* 2017], presenting other water-associated targets for life detection.

Life Detection Strategy

The most robust strategy for searching for life in extraterrestrial environments would be to employ several techniques on a mission to corroborate the detections/non-detections, as recommended by the Europa Lander Science Definition Team Report [*Hand et al.,* 2016]. Possible techniques include: chirality ratios, electron-transfer/redox gradients/disequilibrium, long-chain polymer detections, physical morphology characterizations, and organic detections. Multiple indications of life using disparate techniques could dispel ambiguity and increase confidence in results. We suggest that one such measurement would be to analyze for Long

Chain Polymers (LCPs). Several groups have demonstrated a variety of synthetic LCPs that can encode information [*Al Ouahabi et al*., 2017], so broad technologies that can assess different LCPs would be desirable. DNA and RNA are exemplar contributory signals of life: these polymers are known to transfer heritable information down across generations in terrestrial organisms and could act similarly elsewhere. *Also of high value in this analysis, DNA/RNA detection and sequencing could help rule out doubt that a detection was actually terrestrial contamination*.

LCPs such as DNA and RNA fall on a high rung of NASA's Ladder of Life (https://astrobiology.nasa.gov/research/life-detection/ladder/), indicating high applicability to extant life if detected. Although the Ladder states a high probability for a false positive (contamination), with characterization/sequencing and proper controls in addition to detection alone, this issue could be mitigated. The challenge of detectability can be addressed through the sample preparation process and instrument application as described below. These are areas we highlight here as having some development but with further development needed by the field.

Instrumentation Development

Nanopores for LCP Detection. Traditional sequencing and identification of organisms through their LCPs currently requires the use of large, complex machines. Novel, small, low-mass and low-power nanopore devices have been developed commercially that can detect, and in some cases, characterize LCPs including DNA, RNA and proteins as they pass through the pore. The MinION nanopore sequencer by Oxford Nanopore Technologies Ltd (ONT) is small and portable, the size of a USB flash-drive, suitable for planetary application (W 105mm x H 23mm x D 33mm, weight of 103g, ~ 1W power). The MinION has detected and sequenced DNA and RNA from low biomass samples with certain sample preparation steps [*Mojarro et al.*, 2017]. Nanopore sequencing identifies DNA directly, by detecting a change in current level as the DNA strand passes through a nanopore, and is mapped to base pairs. In theory any repeating, structural characteristics discernible by current disruption, can be sequenced, opening the door for the technique to detect a variety of LCPs. Lastly, nanopore sequencing can provide extremely long reads: in the 10-100 kbp range, which preserves the 'genomic context' of where a certain DNA fragment originated from (commercial systems typically sequence in the 30-600bp range). In fact, the maximum fragment length is currently only limited by insufficient sample preparation techniques which fragment the DNA.

One aspect that needs further development for the current MinION device, is the current system's use of protein nanopores with limited shelf life (~few months), which would be untenable for a long-duration mission in extreme spaceflight environments. In addition, the current MinION configurations require binding of LCPs to a motor protein to stabilize its translocation through the pore, in order for signal to be interpretable. Companies are developing synthetic (non-protein) nanopores such that neither library preparation nor protein-binding is required to ensure decipherable translocation. Development of these devices for space flight and integration with a capable sample preparation system would enable a life-detection device with the added capability of differentiating between extraterrestrial life and terrestrial contamination.

Though still preliminary, we have successfully demonstrated the MinION for identifying *Bacillus* species in samples. In addition, we and other users have demonstrated the use of the MinION to sequence low-complexity, metagenomic samples containing several organisms, beyond just pure samples. Furthermore, function of the MinION in microgravity was recently demonstrated aboard the International Space Station [*Castro-Wallace et. al.*, 2017]. These trial results have demonstrated that the measurements needed for planetary sample analysis are feasible with this instrument. Read quality continues to improve, and MinION reads have the huge advantage of losing much less information by preserving the genomic context.

Nanopore Device Signal for LCP Characterization. Nanopore devices offer rich electrical data that is interpreted and called through a neural net-based calling algorithm developed by the company. Typical base calling is done in 5mers, called as each base travels through the pore, thus giving each base the opportunity to be interpreted by the algorithm 5 times, generating better statistical confidence (but not necessarily avoiding systematic error). Calls can be re-compared against the electrical data and the overall data to 'polish' it, and improve quality. Over time, this system has been developed and refined for DNA and now RNA. Intriguingly, electrical data being beamed back from a spacecraft could be interpreted and re-interpreted during and after mission operations, through iteration in a sandbox with candidate LCPs and their variations.

Robust Sample Preparation

Removal/Reduction of Salts and Analyses Inhibitors. Salts are known inhibitors in many sequencing applications. Samples obtained at Europa, Enceladus, Mars and others are likely to contain salts as indicated by remote and *in-situ* observations. Therefore, in order to process samples from these bodies a system must be capable of decreasing the salinity concentration to a level acceptable by the device. An initial test performed on the MinION device by co-author Bradburne found regression of the detection signal with increased salt content (measured as conductivity) as beginning at about 5 mS/cm (~ 4.4 g/kg = 0.4% NaCl). This initial test indicates the need for further quantification tests as concentrations of terrestrial seawater are on the order of 40 mS/cm (35 g/kg = 3.5%) and estimates for the plume ice from Enceladus ranges from 0.5% to 4% [*Hsu et al.,* 2015; *Postberg et al.*, 2009] and Europa's ocean salinities have been estimated as comparable to Earth's. Other inhibitors that could degrade nanopore device performance and may exist in a sample from Europa or Enceladus are ammonium ions, sulfates, sulfuric acid or bisulfate, carbonates, and various irradiated materials [e.g. *Glein et al.,* 2015; *Waite et al.*, 2009; *McCord et al.,* 2002]. To our knowledge, the nanopore device sensitivities to these constituents are unknown.

Concentration of Biomass. Once through the desalination system, the sample may need to be concentrated so that the LCPs are at adequate levels for characterization through sequencing. Currently, the most common way to concentrate biomass from dilute samples is through centrifugation. A novel method, Synchronous Coefficient of Drag Analysis (SCODA) [*Pel et al.*, 2009; *Bradburne*, 2014] can concentrate LCPs, including DNA, from complex matrices such as soil and prepare the sample for sequencing by removing amplification inhibitors, all with few to no moving parts [*Bradburne et al.*, 2012]. Amplification is needed when biomass levels are low for traditional sequencing machines, although a nanopore sequencer may be able to detect much lower levels. Previously, the desalination and SCODA techniques together enabled successful extraction of DNA from low-biomass planetary analog samples, containing salts and molecular assay inhibitors, where other studies detected little to none. Samples were processed from the Atacama Desert [*Neish et al*., 2012; *Bradburne et al.*, 2012], a Norwegian glacier [*Craft et al.*, 2014], and from aerosol filters collected on a JHU APL rooftop in Laurel, MD. Norwegian glacier samples were collected and deposited on filters in 2009 as part of the NASA SLIce effort (Signs of Life in Ice); however, extraction of characterizable DNA was unsuccessful. Remaining filters, provided by Dr. Jennifer Eigenbrode of the SLIce team at NASA Goddard, were processed and successfully extracted and characterized DNA including identification of extremophiles and human contamination. Results shown in Figure 1 for Filter A (surface core section) emphasize the need for the SCODA step and indicate improved extraction when SCODA is followed by a second purification and desalination with Serapure, as increased DNA sequencing reads were acquired (comparison of the 2 left-most blue columns in Figure 1). Serapure is a process that removes salts by adding the sample to a strongly charged solution containing carboxyl-coated silica beads with magnetic cores. These results are significant, considering that biomass at rover/probe-accessible locations will also likely be extremely low in abundance, if present at all. The SCODA system currently has a form factor similar to a desktop computer (about 45 x 60 x 70 cm^3) and requires >1000W power. Miniaturization and power reduction will be required prior to spaceflight.

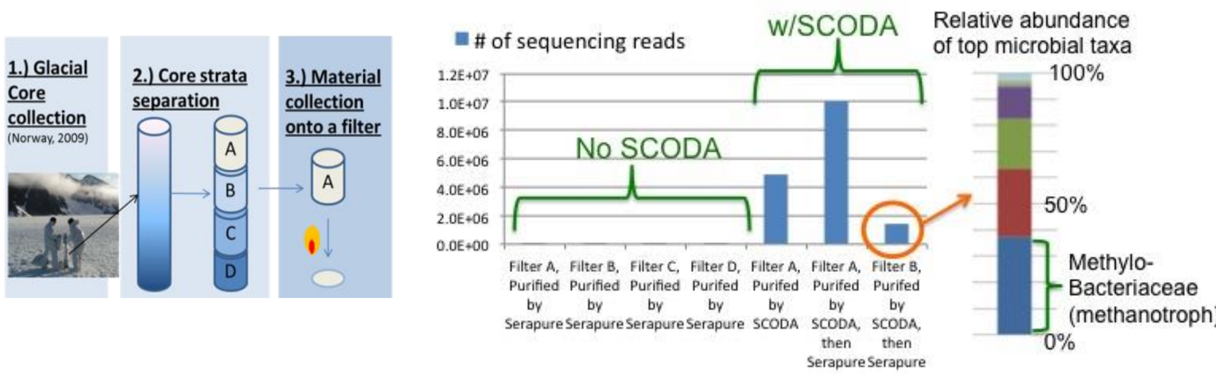

Figure 1. DNA sequencing results for extraction from a Norwegian glacier sample (sample provided by NASA Goddard [*Eigenbrode et al.*, 2009]), showing the ability of SCODA for improved extraction that enables identifications of organisms in complex samples.

Additional Applications of LCP Detection Device

Another important astrobiology application of a LCP characterization device would be enabling investigations into how terrestrial organisms taken into space change within those environmental conditions. Increasing our understanding of biological changes and adaptations to micro-g, radiation, vacuum and different pressures, extreme temperature swings, etc. would provide insight into life that may have evolved on other bodies in our solar system. The technique would also provide a means to investigate planetary protection concerns for mutating organisms accidentally sent along on a planetary mission. Last, if humans are truly to explore the outer regions of space we will someday need to understand how the DNA and RNA of plants and animals may mutate during long-duration space flight.

Summary

Detection of LCPs, including DNA, would provide one technique for biosignature observation and corroborate life detection with other biosignature detection techniques. Also, the LCPs, namely DNA, could be sequenced to enable identification of contamination by human-associated microbes or residues. This, along with robust sample preparation that can remove salts and retain low biomass levels and meet instrumentation size and power requirements, would provide a huge step forward in the capability to send instruments to investigate the Ocean Worlds and other planetary bodies for life. As shown in previous studies, outside contamination in these analyses is hard to prevent [*Eigenbrode et al.*, 2009]. With the increasing ability to detect organisms at sites containing only trace levels of biomass, these considerations become even more important to ensure detections of biology are of truly those at the site and were not “brought along”. Additionally, low contamination is essential to prevent saturation by a contaminant that overwhelms and prevents detection of a trace biosignature. LCP detection techniques could also be used to ensure planetary protection for spacecraft, and be applied in experiments to investigate how terrestrial organisms in space change over time within those environmental conditions.

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Follow the plume: Organic molecules and habitable conditions in the subsurface ocean of Enceladus

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1. Enceladus: organic chemistry in a habitable ocean

Are we alone in the Universe? The search for life beyond Earth is the most compelling scientific question of our time; a positive detection would be one of the most profound discoveries ever made by humanity. Chemical evidence of habitable conditions and organic compounds make Saturn's moon Enceladus a promising lead in the search for life beyond Earth.

In 2005 Cassini's Imaging Science Subsystem (ISS) discovered a plume of gas and icy particles venting into space over the South Polar Terrain (SPT) of Saturn's icy moon Enceladus (**Fig 1**) [1–5]. The SPT is a region dominated geologically by large rifts in the icy crust, informally called 'tiger stripes.' The plume erupts along active fractures as diffuse curtains of material, with localized regions of enhanced eruption, called 'jets' [3,6,7]. Sources of jets and curtains along vents coincide with the warmest regions of the fracture system [3,6], and the plume varies in brightness with orbital position [8]; it is likely that tidal stress along the tiger stripes modulates its eruption activity with a maximum output when Enceladus is furthest from Saturn [9]. Erupted material is the source of particles that make up Saturn's E-ring [5] first observed in 1966 [10], but mantling materials over the SPT [1] point to plume fallout deposits at least several meters thick, or $>10^3$ years old considering deposition rates between 10^{-2} and 10^{-3} mm/yr [11]. The actual longevity of the plume could be $>10^4$ and perhaps $>10^6$ years, assuming the E-ring is a source of oxygen compounds in Titan's atmosphere [12], and of mantling materials on the surface of Helene .

Plume emissions consist of icy particles and vapor originated in an ocean of liquid water 10 km deep, located 30-40 km beneath the moon's surface [13–15]. Cassini flew by Enceladus 22 times, spatially resolving the structure and composition of the plume [13,16–19]. During the second flyby (E2) at high altitude (>150 km) and high speed (>15 km/s), the Ion Neutral Mass Spectrometer (INMS) detected gaseous H_2O and CO_2 [13]. During lower flybys (<50 km altitude, <10 km/s) (E5, E14, E17, E18), INMS also detected H_2, CH_4, HCN, methanol, formaldehyde, $C_{2\text{-}4}$ alkenes, $C_{2\text{-}5}$ alkanes, and benzene [13,14,19]; and the Cosmic Dust Analyzer (CDA) detected icy particles containing sodium and potassium salts [18] and refractory organics [17]. Salt-bearing particles are found to dominate the total mass flux of ejected solids (>99% by mass), but are depleted in the population escaping into the E-ring [18]. While the abundance of sodium in salt-bearing particles is fairly consistent (~0.5-2% by mass) [15,18], the abundance of total organics appears to range dramatically from a few parts per million (ppm) in some particles to 50% by mass in others [18]. The CDA also found silica nanoparticles in the E-ring that were linked to ongoing, alkaline hydrothermal activity at the ocean-sediment interface [20,21] reminiscent of hydrothermal vent systems in Earth's deep oceans. Ocean temperatures likely range from ~0°C near plume sources to ~90°C at the hydrothermal vents, and recent geochemical models of the ocean indicate an alkaline pH of ~11-12 (Glein et al. 2015), but estimates range from 6 to 12 [22–24]. Collectively, these observations are suggestive of a subsurface ocean in contact with the moon's rocky core [13,15,20,21].

Cassini provided a snapshot of a familiar, and yet alien, world that has many of the components—internal heat, an extensive liquid-water ocean, organics, and geochemical cycling—necessary to support an extant biosphere. In this white paper put forward a series of specific recommendations to the next NASA Astrobiology Strategy emphasizing key science investigation of the Enceladus plume (and any other plume discovered in the future) and the technology needed to achieve them.

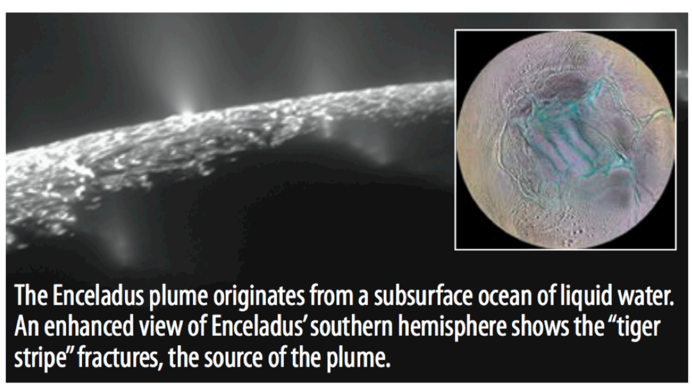

Figure 1. Enceladus has a subsurface ocean with the necessary conditions to support life. Its plume of icy particles and gas provides a unique opportunity to investigate the ocean without descending into it. Image credit: NASA/JPL

2. Science goal: The origin of organic molecules in the subsurface ocean of Enceladus

One of NASA's most immediate priority goals should be to define a science strategy to determine the origin of organic molecules in the subsurface ocean of Enceladus. Once defined, this science strategy would become the foundation on which to build mission enabling technologies in the next 10 years. Based on previous recommendations [25–30], the origin of organic molecules in a given environment is best determined through chemical and structural analyses of different classes of organic compounds, such as patterns in molecular carbon number, isotopic ratios, dominant presence of specific molecular structures, etc. However, there is limited literature and even less consensus on the range of possible chemical and structural solutions—the chemical space—expected to exist in a subsurface ocean such as Enceladus. There is also little consensus on what specific molecular patterns, isotopic ratios, structures, etc. would be indicative of biotic or abiotic sources of organic compounds. Given the likelihood of a mission that investigates the organic chemistry of the Enceladus' ocean within the next 20 years, it is imperative that the broader astrobiological community agrees upon a "set of rules" on what would constitute evidence of abiotic or biotic sources of organic compounds in the Enceladus ocean. This "set of rules" would be better formulated as a series of scientific hypotheses that can be verified or falsified by sample analyses. **We therefore recommend that the next NASA Astrobiology Strategy emphasizes the need for a hypothesis-based framework to assess the origin of organic matter (biotic or abiotic) in the Enceladus ocean**.

3. Key technological challenges

There are three foreseeable technological challenges in the study of organic molecules in the Enceladus ocean: (1) Simulations of plume formation and ejection into space; (2) Sampling the water; and (3) Providing analytical instruments with the best possible sample.

3.1 Simulations of plume formation and ejection

Enceladus is the only icy world known so far to have a sustained plume that samples a subsurface ocean, although hints of plume activity have been observed on Europa using remote imaging [31]. While our reconnaissance of icy moons in the outer Solar System has been limited to a few flythrough missions, plume activity in these bodies could be a common phenomenon. Given the relevance of plumes to investigate the interior of ocean worlds, it is important to understand how plumes form and are sustained through time, and how materials from the ocean, including organic molecules, change when they are ejected into space, due for example to rapid freezing, condensation or UV exposure. This requires both theoretical and empirical studies. Numerical plume simulations based on *Cassini* data have been used to constrain plume dynamics, particle density and particle size distribution [4,32]. We contend, however, that empirical studies would provide the most useful and reliable information, and would also provide analog samples that can be analyzed with prototype technology for future missions. But simulating plumes on icy worlds requires significant technological investment to recreate salt organic laden micrometer sized ice grains at 100 K, travelling at the spacecraft plume flythrough speeds as well as the vacuum and cold temperatures in the space environment. Current *ad hoc* solutions exist [e.g., 32], such as the use of high-speed vertical gun facilities at NASA ARC[*] (**Fig 2**), but these solutions are clearly not optimized. **Therefore, we recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop better "plume simulators", in a way similar to efforts in the past decades to develop "planet simulators" using chambers (e.g., Mars simulation chambers)**.

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[*]https://www.nasa.gov/sites/default/files/files/ames-vertical-gun-range-v2010(1).pdf

3.2 Sampling the plume

In the context of Enceladus, sampling the ocean means an approach to analyze a sample—as small as a few micrograms, and scalable with probable improvements in limits of detection and/or certainty of result up to several grams—of the subsurface ocean. The plume of icy particles emanating from the South Polar Terrains provides direct access to the subsurface ocean without landing on the moon's surface. As discussed in Section 3.1, how closely plume materials represent the composition of the subsurface ocean remains a significant knowledge gap. In addition to natural processes affecting the composition of plume materials, plume sampling technology needs to take into account the stability of organic molecules during sampling. High sampling speeds (i.e. >3-4 km/sec) would cause significant damage to molecules, which could complicate chemical and structural analyses. **Therefore, we recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop plume sampling devices, as well as investigations that seek to understand how organic molecules become altered during plume sampling**. As an example, the ALE3D hydrocode has been implemented at NASA ARC to understand the behavior of ice grains colliding with sample collectors at high speeds. The development of "plume simulators" would be a key component in this effort. In addition, all available models of the Enceladus plume suggest that the amount of material collected after one plume flythrough could be very small (2-5 μL), and therefore microfluidic devices might be needed to handle the fluid, as discussed in the next section.

Figure 2. The Ames Vertical Gun Range (AVGR) is typically used to simulate high-speed, celestial body impacts on a small scale, and recently it has been adapted to simulate plumes emanating from icy moons [33].

3.3 Provide analytical instruments with the best possible sample

The 2015 Astrobiology Strategy singles out certain techniques that in retrospect are relevant to the investigation of organic compounds in the Enceladus ocean, including melting and filtration of ice, followed by ultra-sensitive analysis using various chemical techniques such as immunoassays, lab-on-a-chip methods using capillary electrophoresis and laser induced fluorescence and ultra-sensitive mass spectrometry. However, it obviated the fact that in the case of plume samples, instruments must be able to handle tiny sample volumes (2-5 μL), and these sensitive analytical tools often require different sample handling and preparation functions, including: (1) Integrated pumping, metering, valving, and control of flow rate and pressure; (2) Filtering non-soluble particles by size; (3) *In-situ* measurement and adjustment, up or down, of both ionic strength (conductivity) and pH; (4) Admixture of reagents such as dyes, stains, and fluorescent labels; (5) Degasing and trapping of bubbles; (6) Distributing appropriately preprocessed sample aliquots to analytical instruments at the appropriate flow rate and total fluid volume, with repeat aliquots for redundant analyses that will increase the statistical power of the results.

Technology for handling and preparation of small liquid samples in the environment of space is still incipient. Over the past decade, NASA ARC has developed, space qualified, and operated a range of bioanalytical / bioprocessor systems that comprised the payloads of multiple nanosatellite missions to study living biological organisms in Earth orbit [34–37]. More development is needed to adapt these existing technologies, or invent new ones, for long-term Astrobiology missions to investigate plumes in the outer Solar System. **Therefore, we recommend that that the next NASA Astrobiology Strategy emphasizes the development of front-end microfluidic technology to handle and prepare small volumes of liquid samples, with the goal of maximizing the performance of back-end analytical systems.**

3.4 Contamination Control

Due to the low organic abundances expected in the Enceladus ocean [38], any mission that seeks evidence of life in plume materials must implement stringent cleanliness and contamination control protocols at all mission levels to prevent a false positive results. Here, contaminant material refers to any organic compound classes that are targeted by the mission, such as amino acids, which were not originated in the Enceladus ocean, and include terrestrial sources as well as other possible sources between Earth and Enceladus. We note that the required contamination plan will likely have to go beyond standard planetary protection requirements that are concerned with the transfer of viable terrestrial organisms, since non-viable terrestrial organisms could still be a source of organic material and cause a false positive result. **We recommend that that the next NASA Astrobiology Strategy emphasizes the need to define an adequate contamination control strategy to sample and analyze the Enceladus plume and also captures the need to fund and develop the technology necessary to implement that strategy.**

4. Summary of recommendations

-We recommend that the next NASA Astrobiology Strategy emphasizes the need for a hypothesis-based framework to assess the origin of organic matter (biotic or abiotic) in the Enceladus ocean.

-We recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop better "plume simulators", in a way similar to efforts in the past decades to develop "planet simulators" using chambers (e.g., Mars simulation chambers).

-We recommend that that the next NASA Astrobiology Strategy emphasizes the need for technology funding to develop plume sampling devices, as well as investigations that seek to understand how organic molecules become altered during plume sampling.

-We recommend that that the next NASA Astrobiology Strategy emphasizes the development of front-end microfluidic technology to handle and prepare small volumes of liquid samples, with the goal of maximizing the performance of back-end analytical systems.

-We recommend that that the next NASA Astrobiology Strategy emphasizes the need to define an adequate contamination control strategy to sample and analyze the Enceladus plume and also captures the need to fund and develop the necessary technology to implement that strategy.

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Life Beyond the Solar System:
Observation and Modeling of Exoplanet Environments

A white paper submitted in response to the NAS call on the Astrobiology Science Strategy for the Search for Life in the Universe

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The search for life on planets outside our solar system has largely been the province of the astrophysics community until recently. A major development since the NASA Astrobiology Strategy 2015 document (AS15) has been the integration of other NASA science disciplines (planetary science, heliophysics, Earth science) with ongoing exoplanet research in astrophysics. The NASA Nexus for Exoplanet System Science (NExSS) provides a forum for scientists to collaborate across disciplines to accelerate progress in the search for life elsewhere. Here we describe recent developments in these other disciplines, with a focus on exoplanet properties and environments, and the prospects for future progress that will be achieved by integrating emerging knowledge from astrophysics with insights from these fields.

This is one of 5 "Life Beyond the Solar System" white papers submitted by NExSS. The other papers are: (1) *Exoplanet Properties as Context for Planetary Habitability;* (2) *Technology Development for Continued Progress;* (3) *Remotely Detectable Biosignatures;* (4) *Exoplanetary Space Weather and Habitable Worlds.*

1. Areas of significant scientific progress since publication of the NASA Astrobiology Strategy 2015

A. Exoplanet Observations

Most recent observational advances are covered by the companion *Exoplanet Properties* white paper. Here we note major developments since AS15 that are relevant specifically to exoplanet environments and habitability:

i. The first identifications of potentially habitable nearby Earth-size planets: Proxima Centauri b [1], TRAPPIST-1 e (and perhaps f,g) [2], and LHS 1140 b [3].

ii. The discovery that atmospheres can be retained on short-period rocky exoplanets despite a hostile stellar environment (GJ 1132 b) [4].

iii. A gap in the radius distribution of close-in Kepler planets that documents planets with atmospheric photoevaporative loss and planets that formed gas-poor [5].

iv. Mass-radius diagrams for planets with both RV and transit detections that differentiate rocky, Neptunian, and gas giant planet regimes [6].

v. Categorization of planets by susceptibility to various escape mechanisms to infer exoplanets with vs. without atmospheres [7].

vi. Possible first evidence for ongoing geological activity/surface lava exposure on an exoplanet (55 Cnc e) [8].

B. Exoplanet Modeling

i. Since AS15 there have been advances in identifying false positives for biosignatures, frameworks for biosignature assessment, and statistical/quantitative approaches. The NExSS Biosignatures Workshop in 2016 led to 5 papers on these topics. See the companion *Remote Exoplanet Biosignatures* paper for more details.

ii. The concept of habitable planets has been expanded to include greater consideration of high-energy radiation from the host star, in particular ionizing radiation and stellar wind particles and the magnetic field (space weather) and their impacts on atmospheric chemistry and escape [9], [10], [11].

iii. At the time of AS15, most estimates of exoplanet habitability were based on 1D model studies. Since then, 3D Earth global climate models (GCMs) have become widely used tools for understanding factors determining climates and thus potential habitability of exoplanets. These include the role of oceans [12], [13], [14], effects of partial land coverage [15], [16], cloud stabilizing effects as a function of planet rotation [17], [18], and differences between planets orbiting cool vs. warm stars [19], [20]. 3D models are now routinely used to create synthetic transit transmission spectra and phase curves [16], [19], [20], [21] to inform the interpretation of exoplanet observations.

iv. Since the New Horizons flyby of Pluto in 2015, considerable evidence from observations and modeling implies that long-duration high-volume subsurface water oceans are a very common feature for icy trans-Neptunian object analogs, icy outer moons, and planets not bound by host stars (Nomad planets) [22], [53], [54], [55].

2. Promising key research goals in the field of the search for signs of life in which progress is likely in the next 20 years

A. Factors affecting the potential for life on planets orbiting M dwarfs

Most rocky planets that will be discovered by missions such as TESS and ground-based telescopes (e.g., MEarth, E-ELT), or characterized by transit transmission spectra acquired by JWST, in the next 20 years will be close-in tidally locked objects orbiting cool stars. The highest priority for cross-discipline studies will be to understand the physical processes that make these planets more or less promising for habitability than more Earth-like planets orbiting warmer stars, to determine optimal M star candidates that minimize the deleterious effects of the stellar environment, and to begin to characterize rocky planets orbiting such stars. Steps to achieve these goals include

i. Modeling the impact of pre-main sequence elevated luminosity [23], [24] and energetic particles [9], [10] on the retention of atmospheres, and specifically water [25], for a variety of planets.

ii. Understanding the factors that determine the strength of tidal heating and global magnetic fields and their impact on exoplanet habitability [26], [27].

iii. Constraints on spin synchronization: Recent research utilizing advanced geophysical interior modeling finds capture into exact 1:1 spin-orbit resonance may not be as common or inevitable as previously thought for close-in terrestrial planets [49], [52]. Equilibrium at higher order (e.g., 3:2) spin-orbit resonances must be given strong consideration in climate models [14]. Pseudo-synchronous states (e.g., 3% faster than synchronous) are now believed likely for worlds with liquid layers [50], and unlikely for solid worlds [51]. Most importantly, atmospheric torques even for thin atmospheres are now found to be sufficient to break typical 1:1 spin-orbit resonances [28].

iv. Modeling the effects of ionizing radiation of planet-hosting stars on the initiation of prebiotic chemistry on rocky exoplanets [11].

B. Greater utilization of short time scale 3D global climate models and geologic time scale carbonate-silicate cycle and planetary interior models to simulate the potential habitability of exoplanets for all stellar types

i. 3D GCMs will be applied in several ways: (1) Broadly, to understand the limits of and optimal conditions for habitability [18], and to help prioritize promising targets for characterization among the large number of habitable zone planets found by TESS and ground-based telescopes. (2) Narrowly, to simulate the detectability of biosignatures for specific exoplanets of interest (TRAPPIST-1, Proxima Centauri b, LHS 1140 b etc.) [16], [20], [21]. (3) To explore potential synergies between the more easily characterized atmospheres of giant exoplanets [29] and those of harder to observe rocky planets. The goal will be to identify features that are robust across a variety of models.

ii. Planetary evolution over geological/astronomical time will be quantified, including changes in radiogenic heat flux [29], modes of tectonism [30], tidal activity [26], [27], and associated effects on long-term planetary habitability [31], [32]. This includes improving understanding of interior-atmosphere connections [33], tidal-orbital feedback [26], and how planets with greater or less geologic activity (e.g., volcanism), or differing modes of tectonism (e.g., plate tectonics vs. stagnant-lid) lead to variations in habitability by altering chemistry, surface temperature [32] or surface water availability [34]. Questions about how the carbonate-silicate cycle operates on geologic time scales to regulate surface temperature [35], whether it can efficiently regulate CO_2 on global ocean “aquaplanets” [36], and whether aquaplanets have reduced primary productivity [37] that affects biosignature detectability [38] will need to be addressed.

iii. Solar system objects will be used to test and constrain exoplanet models and theories. Examples include global magnetosphere-ionosphere-thermosphere models to study the impact of extreme space weather on Earth, Mars and Venus [11], [39], the “cosmic shoreline” theory of atmospheric retention [7], tidal maintenance of subsurface water on Europa and Enceladus [40], [56], and mechanisms that may explain habitable conditions on the terrestrial planets under the faint young Sun [41], [42], [43], [44], [45].

iv. Laboratory work will be conducted to better understand atmospheric processes and their effect on temperature structure and spectra, especially for extreme temperatures and pressures and exotic species characteristic of hot gaseous planets and the early histories of rocky planets: Gas opacities, chemistry, cloud formation. [46]

v. Laboratory experiments to determine whether energetic particles and cosmic rays can compete with known mechanisms for the formation of hazes and clouds [47].

C. Biosignature studies (see the companion *Remotely Detectable Biosignatures* paper).

3. Key technological challenges in astrobiology as they pertain to the search for life on exoplanets

i. It has now become feasible to conduct large ensembles of 3-D Earth climate model simulations. Such ensembles for exoplanets, sampling the full range of potentially observable external parameters (rotation, instellation, etc.) as well as difficult to observe internal parameters (surface pressure, greenhouse gas concentrations, etc.) may help to identify the parts of the space most favorable to habitability, perhaps with the aid of machine learning approaches that detect optimal parameter combinations.

4. Key scientific questions in astrobiology about the search for life on exoplanets

i. What biogeochemical and climatic factors determine the robustness and remote detectability of exoplanet life? A wide range of environments may support life, but to detect it remotely, we need to understand the processes that favor abundant life with strong, unambiguous biospheres. These include interior processes that control geochemical fluxes of gases, biosphere robustness on aquaplanets vs. planets with continents, external parameters that control the spatial extent of clement temperatures and surface water availability, conditions that produce clouds or hazes that will confound attempts to detect biosignatures, and false positives that may mask biotic signals.

ii. Do planets build up thick CO_2 atmospheres through the carbonate- silicate cycle feedback at cold temperatures? The outer edge of the habitable zone for “Earth-like” planets is defined by extrapolating the carbonate-silicate cycle feedback that seems to occur on Earth to cold temperatures [57], implying the buildup of many bars of CO_2. A challenge for the coming two decades will be to observationally constrain the extent to which this process operates on planets irradiated more weakly than Earth [48].

iii. What atmospheric properties (e.g., temperature structure, chemical abundances, circulation regime) of more easily observed large exoplanets (Jupiters to sub-Neptunes) can be observationally constrained by near-future missions? These planets may in some respects serve as a testbed for theories about the atmospheres of rocky exoplanets that are more challenging to observe [14], [58].

5. Scientific advances that can be addressed by U.S. and international space missions and relevant ground-based activities

i. TESS will greatly expand the population of known potentially habitable exoplanets, some of which may be selected for atmospheric characterization by JWST mid-IR transit transmission and eclipse spectra to search for H_2O or biosignature gases. Other JWST contributions are discussed in the *Exoplanet Properties* white paper.

iii. Extreme Precision (10 cm s^{-1}) Radial Velocity measurements [49] will allow minimum masses to be estimated for a larger number of rocky exoplanets with radius estimates already obtained from transits, thus allowing planet densities to be estimated.

iv. ELTs and other ground-based platforms will greatly expand the list of rocky planets orbiting ultracool stars and characterize the atmospheres of some of them.

v. WFIRST will demonstrate the coronagraph technology for a future direct imaging mission that would study Earth-like planets, if total mission cost can be limited.

6. How to expand partnerships (interagency, international, public/private) to further the study of life's origin, evolution, distribution, and future in the universe

i. The search for life is now the 10th agency-wide objective of NASA. It includes the search both within and beyond the Solar System, and these have some overlapping objectives. The current organization of the Science Mission Directorate (Planetary, Astrophysics, Heliophysics, Earth Science) results in unintentional barriers to cross-disciplinary work required for the search for life. Given the emphasis on such activities at the agency level, SMD should consider restructuring or expanding its programs.

ii. Increasing the rate at which innovative multi-disciplinary, inter-agency, and/or international projects are launched is a high priority. Physical centers/ hubs for short/ medium-term visitor programs (1-6 months) with daily talks and regular social events have a successful track record in jump-starting novel, high-impact new collaborations (Institutes for Advanced Study worldwide, Harvard's Radcliffe Institute, etc.).

iii. New launch vehicles and optical design, fabrication, and testing technologies are needed to enable innovative, very large-aperture space-based telescopes or arrays. Much larger apertures will provide greater light-gathering power, essential for studying a larger sample of transiting exoplanets and increasing the sample of directly imaged planets. (Private enterprise builds most missions managed by NASA.)

A procedure for observing rocky exoplanets to maximize the likelihood that atmospheric oxygen will be a biosignature.

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Introduction

The search for life on planets around other stars is one of the grand scientific challenges of the 21st century. The approach being adopted by the astronomical community is to find putative biosignature gases—especially oxygen or methane—in the atmospheres of such planets, through infrared transmission or emission spectroscopy (Domagal-Goldman, Wright et al. 2016). To detect these biogases using transit spectroscopy will require at least the sensitivity of the James Webb Space Telescope (*JWST*), to be launched in 2019. It appears possible to use *JWST* to characterize the atmospheres of many known transiting rocky exoplanets around M stars (Morley et al. 2017), but there are likely to be many more habitable planets to characterize than *JWST* can observe.

The astronomical community therefore must plan these observations carefully, in terms of target selection and interpretation. The Transiting Exoplanet Survey Satellite (*TESS*) will find dozens of transiting exoplanets in their star's habitable zones (Sullivan et al. 2015), and a strategy will be needed to prioritize them for follow-up *JWST* observations. From nearby stellar population statistics and Kepler planet frequency results (Mulders et al. 2015), most (perhaps all) transiting rocky exoplanets likely will be found in the habitable zones of M dwarfs (e.g., Trappist-1e; Gillon et al. 2017), with water contents possibly much greater than Earth. Such planets appear more prone to false positives for oxygen (e.g., Luger & Barnes 2015). Modeling will be needed to interpret whether oxygen is a true biosignature on various exoplanets, and to prioritize observations of exoplanets.

Here we advocate an observational strategy to help prioritize exoplanet observations. It starts with more easily obtained observational data, and ranks exoplanets for more difficult follow-up observations based on the likelihood of avoiding planets for which oxygen is a false positives or even an inconclusive signature of life. We find that for oxygen to be a robust biosignature, both land and surface water must be present. Landless exoplanets have much slower biogeochemical cycles, so while oxygenic photosynthesizing life could exist on such planets, it could not produce oxygen at a rate competitive with abiotic rates such as photolysis. These habitable planets, whose life would not be *detectable*, should be avoided.

Too much water obscures the signs of life

Life as we know it requires water, and water is equated with habitability. NASA's mantra in astrobiology has been to "Follow the Water". We recently presented work at the November 2017 Habitable Worlds Meeting demonstrating that too much water is detrimental to oxygen production by life (Desch et al., in preparation). On an Earth-like planet with 50 oceans (~1 wt% bulk H_2O), continents and geochemical cycles take place under a thick (~100 km) high-pressure ice mantle, cut off chemically from the oceans; the pressure of 100 oceans (~2 wt% H_2O) can suppress silicate melt and stop outgassing and geochemistry altogether (Unterborn & Schaefer, in preparation). Just 5 oceans (~0.1wt% H_2O) are enough to submerge the continents and slow the influx of phosphate (by chemical dissolution of felsic rocks) into the oceans (because of the higher pH of the oceans compared to rainwater), by

2-3 orders of magnitude. This limits the biogenic export of oxygen into the atmosphere to levels comparable to or exceeded by rates of abiotic photolysis and hydrogen escape. **To be certain that oxygen in a planet's atmosphere is biological in origin, one must observe a planet that has both water and land on its surface, i.e., one with < 5 oceans' worth of water (< 0.1wt% H_2O).**

An observational procedure for observing exoplanets

Current techniques can identify planets with > few wt% H_2O, but these should be deprioritized for observations because oxygen will not be a reliable biosignature on them. **Although life as we know it requires water, we should actually search for planets with as little water as possible.** Observations should be undertaken in the order laid out in our flowchart (Figure 1). Here we expand on these steps.

Step 1: Find rocky exoplanets in the habitable zones (HZs) of their stars. Surveys (e.g., by *TESS*) will generate dozens of potential planets. Exoplanets with radii > 1.5 R_E should be excluded because they are likely to have thick H_2/He atmospheres (Weiss & Marcy 2014). Exoplanets in multi-planet systems (e.g., Trappist-1) may be preferred, as masses can be much better refined by transit timing variations (TTVs), In the next 15 years, these selection criteria will highly favor exoplanets around M dwarfs (Charbonneau 2017).

Step 2: Determine the current X-ray/ultraviolet (XUV) fluxes and infer the past XUV fluxes of host stars. Flux values exist in the ROentgen SATellite (ROSAT) All Sky Survey catalog, and new, detailed measurements, at least down to 0.1 keV, can be obtained using Chandra or X-ray Multi-Mirror (XMM) observatories. Stars with insufficient past activity to strip H_2/He atmospheres should be excluded, as these atmospheres will prevent a determination of water content. All the Trappist-1 planets easily could have lost $\sim 10^{-2}$ M_E of H_2/He atmosphere over 8 Gyr assuming Trappist-1's current XUV flux, much greater than the masses of H_2/He gas accreted from their nebula, $\sim 10^{-3}$ M_E (Unterborn et al., in revision). The XUV flux also should not be consistent with abiotic O_2 buildup by hydrogen escape. Luger & Barnes (2015) find that fluxes must exceed a critical limit so that O_2 generated by H_2O photolysis escapes along with the hydrogen. The XUV fluxes must exceed both limits.

Step 3: Measure the planetary masses and radii as precisely as possible. Radii determined from precise photometry will probably not be as uncertain as the masses. Masses should be derived from RV measurements, but since most of the host stars are likely to M dwarfs, TTVs likely will be the stronger constraints on planetary mass, which is why multi-planet systems might be preferred.

Step 4: Obtain stellar abundances. Modeling the mass-radius relationships of exoplanets requires determining the likely range of bulk Fe/Mg the planet might have. The planetary Fe/Mg ratio is the stellar Fe/Mg ratio, modified by estimates of mantle stripping and disk processes. We find that variations across the range of observed stellar compositions (Fe/Mg = 0.4 to 1.5) lead to 20% variations in the mass and density. In principle, < 1wt% H_2O abundances could be inferred if the

Fe/Mg ratio were constrained to < 5% or 0.02 dex. This precision is unlikely, but the more precisely the composition is determined, the better.

Other stellar abundances (Mg/Si, Na/Si, K, U, Th) also can provide very important geophysical context, as their abundances in the planet set the vigor of mantle convection, and possibly plate tectonics. These could help prioritize or de-prioritize planets for observations, in concert with sophisticated geophysical modeling.

Step 5: Conduct sophisticated modeling to find the probability that the observed mass and radius of the exoplanet is consistent with "no" (< 0.1wt%) water. Part of this modeling must include new equations of state for rock-water alloys at high pressures, and non-Earth-like compositions. As exoplanets are observed and placed in the mass-radius diagram, those lying above the mass-radius curve for waterless planets (i.e., less dense than pure rock/metal planets) must be inferred to have abundant H_2O. Those lying furthest below the curve (in sigmas, the observational uncertainties in mass and radius) are most likely to be waterless planets. Those should be prioritized for further observation.

Step 6: Perform low-spectral-resolution optical transmission spectroscopy to determine the transit depth as a function of color. A lack of variation (as for GJ1214b: Kreidberg et al. 2014) would indicate either the lack of an atmosphere or the presence of hazes. Since observation of the surface is demanded (and of course life needs an atmosphere), only those exoplanets with some variation in transit depth with color should be further characterized.

Step 7: Perform high-spectral-resolution infrared transmission spectroscopy. At this step the sought biosignature oxygen could be detected. H_2O vapor also is detectable and should be found, to signal the presence of liquid water on the surface. CO_2 is likely to be present and detected, but if CO_2 is present at $\sim$ 1 bar levels, this would indicate a breakdown in the carbonate-silicate cycle, suggesting a dearth of bioessential elements, de-prioritizing the planet for further observations.

Step 8: Obtain the optical reflectance light curve. If and only if the previous steps have indicated a planet with relatively little water—an atmosphere with oxygen, and signs of liquid water on the surface—should the an attempt be made to measure the optical reflectance light curve. Reflected light may be used to find evidence of glint, supporting the presence of liquid water on the surface (Williams & Gaidos 2008), but the most important role of light curve analysis is to identify land. Principal component analysis of the time-varying reflected light in various filters has detected land and oceans on Earth, and could identify patches of land, ocean, and vegetation (Cowan et al. 2009; Fujii et al. 2010).

The procedure outlined above allows observers to start with observations of planetary mass and radius and stellar XUV flux and elemental abundances, and then prioritize only the most promising planets for the more difficult, time-consuming observations involving spectroscopy and reflectance light curves. Presumably all planets observed would be habitability; those with surface water and land would be favored, so that oxygen could be the most robust biosignature if detected.

This exercise highlights potentially mutually exclusive selection criteria. For example, HZ exoplanets around M dwarfs are favored for atmospheric measurements, for the likelihood they transit and the transit depths. But optical light curves are more easily obtained for HZ exoplanets around FGK stars, as M star HZs are within the inner working angle of most telescope designs. Elemental abundances of M dwarfs also are difficult to obtain. These and other factors may need to be weighed against each other in mission development and design.

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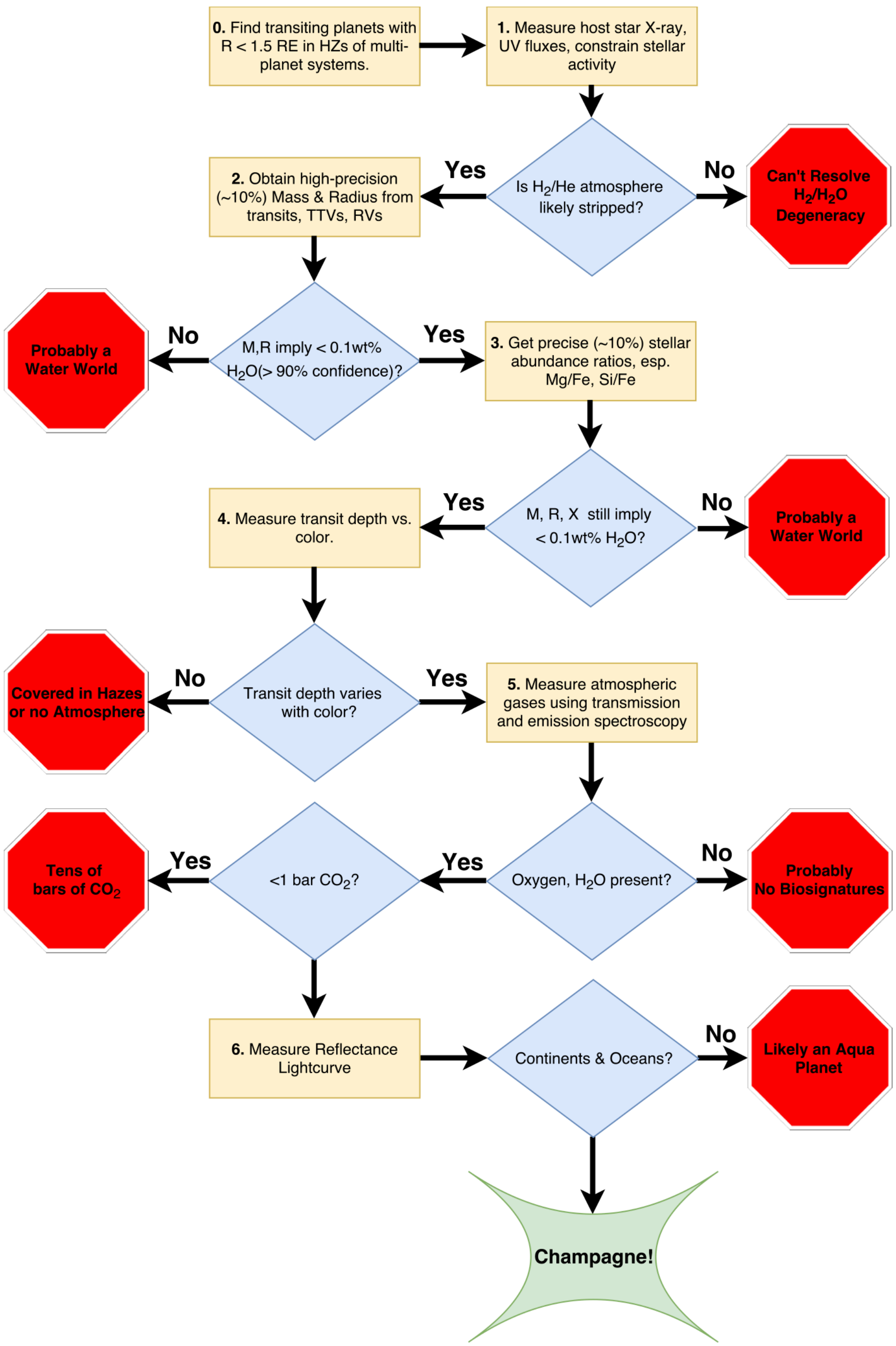

Figure 1: A flowchart describing the observational campaign being advocated here, designed to find not just planets with oxygen in their atmospheres, but planets for which oxygen also would be a biosignature. The observations range from those currently being undertaken, to those requiring future space missions and possible for only a handful of exoexoplanets.

Life Beyond the Solar System: Remotely Detectable Biosignatures

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This white paper summarizes the products from the Exoplanet Biosignatures Workshop Without Walls (EBWWW). The following people also contributed to the EBWW. Science Organizing Committee (SOC): Daniel Apai, Shawn Domagal-Goldman, Yuka Fujii, Lee Grenfell, Nancy Y. Kiang, Adrian Lenardic, Nikole Lewis, Timothy Lyons, Hilairy Hartnett, Bill Moore, Enric Pallé, Niki Parenteau, Heike Rauer, Karl Stapelfeldt, Sara Walker. Online and In-Person Workshop Participants: SOC named above as well as Giada Arney, William Bains, Robert Blankenship, David Catling, Charles Cockell, David Crisp, Sebastian Danielache, Shiladitya DasSarma, Russell Deitrick, Anthony Del Genio, Drake Deming, Steve Desch, David Des Marais, Theresa Fisher, Sonny Harman, Erika Harnett, Siddharth Hegde, Yasunori Hori, Renyu Hu, Betül Kaçar, Jeremy Leconte, Andrew Lincowski, Rodrigo Luger, Victoria Meadows, Adam Monroe, Norio Narita, Christopher Reinhard, Sarah Rugheimer, Andrew Rushby, Edward Schwieterman, Nick Siegler, Evgenya Skolnick, Harrison Smith, Motohide Tamura, Mike Tollion, Margaret Turnbull, and Mary Voytek.

exoplanets | habitability | biosignatures | astrobiology

Introduction

For the first time in human history, we will soon be able to apply to the scientific method to the question "Are We Alone?" The rapid advance of exoplanet discovery, planetary systems science, and telescope technology will soon allow scientists to search for life beyond our Solar System through direct observation of extrasolar planets. This endeavor will occur alongside searches for habitable environments and signs of life within our Solar System. While these searches are thematically related and will inform each other, they will require separate observational techniques. The search for life on exoplanets holds potential through the great diversity of worlds to be explored beyond our Solar System. However, there are also unique challenges related to the relatively limited data this search will obtain on any individual world.

This white paper reviews the scientific community's ability to use data from future telescopes to search for life on exoplanets. This material summarizes products from the Exoplanet Biosignatures Workshop Without Walls (EBWWW). The EBWWW was constituted by a series of online and in-person activities, with participation from the international exoplanet and astrobiology communities, to assess state of the science and future research needs for the remote detection of life on planets outside our Solar System. These activities culminated in five manuscripts, submitted for publication, which respectively cover: 1) a review of known and proposed biosignatures (Schwieterman et al., in press), 2) a review of O_2 as a biosignature as an end-to-end example of the contextual knowledge required to rigorously assess any claims of life on exoplanets (Meadows et al., in press); 3) a generalized statistical approach to place qualitative understanding and available data in a formal quantitative framework according to current understanding (Catling et al., in press); 4) identification of needs to advance that statistical framework, and to develop or incorporate other conceptual frameworks for biosignature assessment (Walker et al., in review), and 5) a review of the upcoming observatories - both planned and possible - that could provide the data needed to search for exoplanet biosignatures (Fujii et al., in review). These manuscripts were written by an interdisciplinary and international community of scientists, incorporating input from both an open public comment period and an anonymous journal peer review process. As such, they represent the community-wide scientific consensus on the state of the field, and on the research priorities to further the search for life on exoplanets.

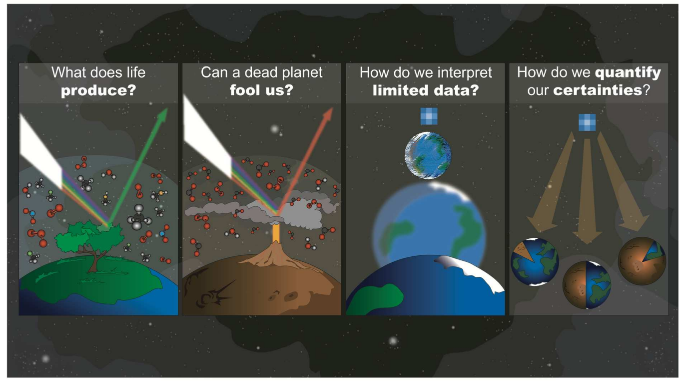

Fig. 1. An overview of the past, present, and future of biosignature theory research. Research historically has focused on cataloguing lists of substances or physical features that yield spectral signatures as indicators of potential life on exoplanets. Recent progress has led to understanding of how non-living planets could produce similar signatures. In the future, the field should strive to utilize what are inherently limited data to deliver quantitative assessments of whether or not a given planet has life. (Credit: Aaron Gronstal)

Progress Since 2015 Astrobiology Strategy

Expanding the library of signs of life. Analyses of a planet's spectrum, even from a single spatial element, can yield information on the presence or absence of chemicals that absorb specific wavelengths of light. It is this limited information upon which many of our proposed biosignatures, as well as other features of the planet's environmental context, must be identified. Much of the history of remote detection of biosignatures focused on spectral features of specific biological byproducts or global phenomena resulting from life. A review of exoplanet biosignatures is presented in Schwieterman et al. (in press), updating a prior review by Des Marais et al. (2002), which was considered in the writing of the Astrobiology Strategy 2015 document. There have been three major developments in exoplanet biosignature science since

2015: the generation of a broader list of potential biosignatures, more comprehensively simulations of these signatures in the context of planetary environments, and consideration of abiotic means through which these signatures could be generated on both living and non-living worlds.

Novel candidate biosignatures. There has been a large expansion in the proposed biosignatures for the community to consider. For photosynthetic pigments, organisms that extend the wavelengths of light that can drive oxygenic photosynthesis have been discovered (Ho et al. 2016; Li et al., 2015), increasing the types of star-planet combinations that can sustain this metabolism (Takizawa et al., 2017). Surface pigments other than those used for oxygenic photosynthesis have also been proposed, including bacteriorhodopsin and other pigments (e.g., Schwieterman et al., 2015a, Hegde et al., 2015). For atmospheric biosignatures, several thousand volatile gases have been identified as worthy of further consideration (Seager et al., 2016). On planets lacking oxygen, atmospheric features such as organic hazes have also been identified as possible signs of life (Arney et al., 2016). Sustained efforts at formal cataloguing of the new wealth of biosignature features are critically needed.

3D simulation of living worlds. Modeling tools have become critical in simulating biosignatures on a global scale. These include photochemical and climate models that can self-consistently simulate these biosignatures within their planetary context. A significant advance in this area since 2015 is the utilization of 3-dimensional (3D) spectral models (e.g., Robinson et al., 2011; Schwieterman et al., 2015b). 3D general circulation models (GCMs) are emerging as important theoretical tools to explore the dynamics of planetary climates and to expand conceptualization of the habitable zone (e.g., Turbet et al.2016; Way et al., 2017). Further development of these modeling capabilities will be needed to apply coupled biosphere-atmosphere processes to simulate biosignatures in a planetary systems science context.

The importance of environmental context. Oxygen-based biosignatures (O_2 and/or O_3) are extremely promising, as they fulfill the three major requirements of a robust atmospheric biosignature: (1) reliability; (2) survivability; and (3) detectability. However, a number of potential "false positives" for O_2/O_3 biosignatures exist, rendering additional environmental context critical for interpreting oxygen-based biosignatures. For example, information about the host star (spectral type, age, activity level), major planet characteristics (size, orbit, mass), and accessory atmospheric species (H_2O, CO_2, CO, CH_4, N_4) can all help to diagnose pathological high-O_2/O_3 cases. Similarly, Earth's atmospheric evolution demonstrates that biogenic gases may remain at undetectable levels despite their production by a surface biosphere (Rugheimer and Kaltenegger, in press).

Planetary characteristics that may enhance the likelihood of such "false negatives" should be considered when selecting targets for biosignature searches. Careful selection of targets can help mitigate against the likelihood of false positive O_2/O_3 signals. For example, selection of older F, G, K or early M dwarf targets (M0-M3) would help guard against false positive O_2/O_3 signals associated with water loss, while potentially increasing the probability that biogenic O_2/O_3 will have accumulated to detectable levels. We suggest an integrated observation strategy for fingerprinting oxygenic photosynthetic biospheres on terrestrial planets with the following major steps: (1) planet detection and preliminary characterization; (2) search for O_2/O_3 spectral features with high-resolution spectroscopy; (3) further characterization and elimination of potential false positives; (4) detailed characterization and the search for secondary biosignatures. The identification of a pigment spectral feature would be a particularly complementary biosignature O_2/O_3 detection, because it would be consistent with the hypothesis that the O_2 was generated by oxygenic photosynthesis. To further improve confidence in identifying surface signs of photosynthesis, the reflection spectra of the mineral background must also be characterized. Newly developed measurements such as the linear and circular polarization spectra of chiral biomolecules can potentially help rule out such false positives. In addition, models that address the surface coverage of a planet are needed to better understand the detectability of these signals.

Scientific Progress in the Next 20 Years

Cross-disciplinary quantitative frameworks. Much of the top-level theory of biosignatures is described in qualitative terms, and the associated advice to mission/instrument design teams is similarly qualitative. For example, we know that the confirmation of biosignatures requires a comprehensive classification of the planetary environment, which in turn leads to a suggestion to obtain observations with as broad of a wavelength range as possible. But evaluation of detailed trade-offs for specific instruments, and eventually the interpretation of data from biosignature searches, will be best enabled by a more quantitative framework.

A major challenge in such quantification is that assessing the presence or absence of life on a planet is an inherently complex problem, requiring comprehensive analyses of the planetary context. And a planet will have multiple systems that interact with each other, often in non-linear ways. Accounting for this in a quantified manner – and doing so in a way that is flexible enough to handle alien worlds with potentially alien climates and potentially alien life - requires an encompassing framework. At the EBWWW, a variety of approaches were discussed, including: process-based planet systems models; quantification of thermodynamic and/or kinetic disequilibrium in a planet's atmosphere (after Krissanssen-Totten et al., 2016); assessment of the complexity of atmospheric photochemical networks (after Holme et al. 2011); and utilization of Bayes' Theorem to assess the data from a single planet or a series of planets. Bayes' Theorem, in particular, was identified as having the potential to advance our field's ability to synthesize sparse data, and as a framework for combining understanding from diverse scientific disciplines.

According to Bayes' Theorem, one can calculate the conditional probability that something is true, such as the likelihood of a system having a given property based on available data. An example mathematical formalism for exoplanet biosignatures is shown in Figure 2, from Catling et al. (in press). This derivation specifically dissects what might be observed (D = data) given either the presence or absence of life within a particular exoplanet environment context (C

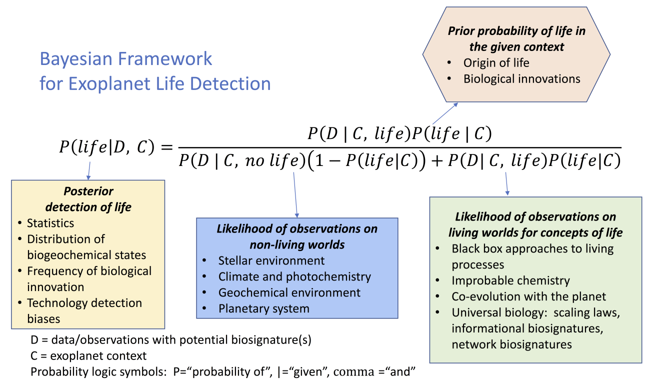

Fig. 2. A Bayesian framework, applied to the detection of life on extrasolar planets. Equation from Catling, et al., in press. Adapted from Walker et al., in review.

= context), i.e., P(data|context and life) and P(data|context and no life), respectively. The conditional probabilities here account for the intertwining of life with its environment, such that they cannot be independent. P(life|context) is a quantitative expression of likelihood of life given the context of the exoplanet, such as amenability to habitability. This is distinct from P(life) (the probability of life occurring at all in the universe). The latter might be estimated from how quickly life emerged on Earth, but is truly quantifiable only with large statistics, after more examples of life have been already discovered, which Walker et al. (in review) expand upon. Bayes' Theorem also provides a means to incorporate uncertainty in data (Parviainen, 2017), additional types and novel concepts of life, such as exotic adaptations, network theory, alternative chemistry, or statistics from ensemble investigations, and in general new data and ideas as they develop (e.g. Deeg et al., 2017). The Bayesian approach thus affords the synthesis of diverse areas of knowledge into a quantitative framework. It also is highly useful for identifying the terms most challenging to quantify. Given the highly interdisciplinary nature of the search for exoplanet biosignatures, adoption of a Bayesian concept is encouraged to help scientists work across disciplines, identify the significance of critical unknowns, and provide quantitative assessments of confidence in scientific conclusions.

The community is beginning to build comprehensive modeling tools, and the future research directions required to quantify our assessments are reviewed in the EBWWW paper by Walker et al. (in review). The tools for simulating data that could come from inhabited/uninhabited worlds are already under development with both flexible 1-dimensional atmospheric models that can be coupled to subsurface and escape models, and comprehensive but less flexible 3-dimensional global climate models. Current work - by large interdisciplinary teams - is increasing the comprehensiveness of the former models as well as the flexibility of the latter ones. This development of models must continue - and the community involvement in their development must be expanded. We also require advancements in chemistry and biology research on life's origins on Earth, and the environments in which life might originate elsewhere, to help with our assessments of P(life). Finally, we must advance our grasp of the likelihood of certain biological innovations, and better understand the full range of metabolisms life can utilize for obtaining energy, beyond those found on modern-day Earth.

Telescopes in Planning or Development

The most critical step in our search for extrasolar life is to detect spectroscopic properties of potentially habitable planets. A handful of Earth-sized planets in the HZs of late-type stars have already been identified (Anglada-Escudé et al., 2016; Dittmann et al., 2017; Gillon et al., 2017), including a few that are close enough for follow-up observation. Soon, discoveries and astrophysical characterization of similar targets will be accelerated by TESS (2018-), CHEOPS (2018-), and ongoing/future ground-based RV surveys. Follow-up observations of such targets could be conducted by the James Webb Space Telescope JWST (2019-), and the next generation ground-based telescopes (GMT, TMT, ELT: 2020s-) and next-generation flagship space telescopes (OST, LUVOIR, HabEx) armed with high-resolution and/or high-contrast instruments. The detectability of the specific features depends on the system properties of the targets as well as the noise floor. And we note that the false positive concerns noted above (as well as concerns about habitability) are greatest for the stellar targets whose planets we will be able to see with this technique. Such concerns should not dissuade us from these observations, but they do make target selection and precursor observations of stellar host properties critical. The characterization of Earth-like HZ planets around Solar-type stars will require more sensitive observations. The PLATO (2026-) mission is specifically targeted at transiting planets in a wider parameter space, including small HZ planets around Solar-type stars. The spectroscopic characterization of potentially Earth-like worlds around Sun-like stars demands space-based high-contrast observations. These observations are not feasible with current and planned facilities, but are among the driving science goals for HabEx and LUVOIR.

Existing and Needed Partnerships

The EBWWW revealed that the search for exoplanet life is still largely driven by astronomers and planetary scientists, and that this field requires more input from origins of life researchers and biologists to advance a process-based understanding for planetary biosignatures. This includes assessing the prior that a planet may have life, or a life process evolved for a given planet's environment. These advances will require fundamental research into the origins and processes of life, in particular for environments that vary from modern Earth's. Thus, collaboration between origins of life researchers, biologists, and planetary scientists is critical to defining research questions around environmental context. Private partnerships - mostly limited to building spaceflight hardware in the past - must expand to improve our computational and modeling capabilities. These collaborations could include the development of generic research tools, as well as specific collaborations to improve or re-write scientific code. This latter area has tremendous potential for new public-private partnerships, as the codes required to quantify our certainty of a biological detection will be complex, and codes with such complexity should be crafted in partnership with professional programmers.

Realizing NASA's astrobiology goals

To realize our goals, and to enable probabilistic assessments of whether or not a planet has life, we require the following developments:

- A more complete incorporation of biological understanding into the field
- Models of fundamental abiotic processes under planetary conditions different than our own
- Evaluation of the wealth of potential new biosignatures, both surface and gaseous, and consideration of their false positives
- An improved capability to predict the expression of photosynthesis in different stellar-planetary environments
- Sustained institutional support to characterize the physical and chemical properties of biogenic small volatile gases
- Development and infrastructure support for 3-D general circulation models (GCMs) for exoplanets, to simulate biosignatures in 3-D
- Expansion of coupling of 1D planetary models for mantle, atmospheric chemistry, climate, ocean, biology, and atmospheric escape processes, with different stellar inputs, to simulate biosignatures in a planet systems context
- More accounting of model uncertainties
- Finally, a Bayesian framework to foster integration of diverse scientific disciplines and to accommodate new data and novel concepts is advocated for further development in the classroom and in collaborative research

That last goal is critical, as a quantitative approach will advance our field in multiple ways. For exoplanet astrobiologists, it will be a powerful way to consider future mission/instrument trade-offs, or to inform future target selection. For our astrobiology peers searching for life on planets around other stars, it will provide a comparative tool with different proposed biosignatures for other targets. For our scientific colleagues beyond astrobiology, it will provide a rigorous test of our conclusions. And for the general public and to stakeholders, it will lead to the ability to clearly and consistently communicate our level of confidence that we are not alone.

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A White Paper for the 2017-2018 National Academies Committee on Astrobiology Science Strategy for the Search for Life in the Universe

For submission January 8, 2017

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

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Over the past decade, evidence for habitable environments beyond Earth has become unequivocal. Regardless of whether or not life established itself in these environments, their existence presents a grand challenge: **Can we identify the rules for planetary evolution, for whether a planet can and does support life?** With the ongoing discovery of terrestrial-type planets around other stars, our own solar system remains the key testing ground for evolutionary models of astrobiological potential, and Mars provides the solar system's longest, earliest record of processes generating habitable environments. We review the discoveries of the past decade and point to the **need for an astrobiological exploration strategy that capitalizes upon Mars' environmental diversity and distinctively long and well-preserved geologic record to both search for life and understand the processes that sustain habitable environments. In the next 20 years, a Mars exploration approach that emphasizes multi-site exploration is required.**

I. Setting the Stage: State of the Science in 2007

Evidence for widespread, long-lived water on ancient Mars was revealed over the period 2004-2006 after decades of prior searching. The first paradigm-changing discovery came from explorations of the Opportunity rover where aqueously altered, sulfate-/hematite-bearing sedimentary strata preserved a record of shallow playa lakes and multiple later episodes of acidic groundwater recharge[1]. The second paradigm-changing discovery came from orbital mapping by the OMEGA instrument aboard Mars Express, which revealed widespread hydrated minerals in rocks from >3 Ga comprising >50% of the Mars surface. Importantly, not only were salts found but also phyllosilicates that required long-term water-rock interaction. The essential question was what did this discovery mean for environments available to potential early Martian life? That is, what geophysical, climatological, and orbital parameters conspired to generate widespread habitable conditions on Mars in the past? And why did these change?

II. Key Finding: The Extraordinary Environmental Diversity of Ancient Mars

The geochemical and environmental diversity of habitats preserved in the rock record from Mars' first billion years was the key finding of the period 2007-2011[2], driven by the Mars Reconnaissance Orbiter (MRO) spacecraft and data from the last years of the Spirit rover mission. MRO revealed thousands of strata with aqueous minerals[3], and a silica-enriched hydrothermal system as well as carbonate bearing olivine-rich rocks were detected by Spirit in situ[4]. Martian rocks preserve evidence for lakes ranging from acid to alkaline (SO_4^{2-}-rich, Cl-rich, CO_3^{2-}-rich or dilute); thick weathering sequences from near-surface waters; volcanic fumaroles;

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[1] *Squyres et al., 2004, Science; McLennan et al., 2005, EPSL; Grotzinger et al., 2005, EPSL; Tosca et al., 2005, EPSL; Edgar et al., 2014, Icarus*

[2] These years also saw a flurry of discoveries about the activity and potential habitability of modern Mars (not discussed here; see other white papers as well as the Mars NEX-SAG report)

[3] *Mustard et al., 2008, Nature; Murchie et al., 2009, JGR; Carter et al., 2013, JGR*

[4] *Squyres et al., 2008, Science; Morris et al., 2010, Science*

deep hydrothermal systems, including evidence for serpentinization; and deep groundwater aquifers with connections to the surface (Table 1).

Table 1. Select Diverse Habitable Environments on Mars [refs. in Ehlmann & Edwards, 2014, Ann. Rev., EPS]		
Deep-water lacustrine	Neutral to alkaline	Jezero crater, Gale crater
	Acid, reducing	Cross crater
	Acid, oxidizing	Columbus crater; Melas basin
Evaporative playas	Chloride dominated	many in Terra Sirenum
	Sulfate dominated	Meridiani Planum
Weathering sequences (saprolites)	high W:R	Mawrth Vallis, Nili Fossae
Weathering sequences (acidic)	Al clay, sulfate	Valles Marineris plateaus
Volcanic hydrothermal	siliceous	Gusev crater; Syrtis Major
Hydrothermal groundwaters	prehnite/chlorite/zeolite facies	many in S. Highlands
Groundwater aquifers (mafic; neutral)	smectite facies	Nili Fossae
Groundwater aquifers (acidic)	jarosite sulfate	Meridiani Plaunum; NE Syrtis
Serpentinizing systems	serpentine, Mg carbonate	NE Syrtis, McLaughlin crater

This ancient rock record offers an unparalleled opportunity to not only discover evidence for life outside Earth but to understand the physical and chemical boundary conditions on habitability. On Earth, the early (>3 Ga) rock record from the time of life's origins and early evolution has been deformed and destroyed by plate tectonics. On Mars, it is available for interrogation.

Key Points	
	• Ancient Mars hosted multiple types of watery environments, varying in space and in time. These were habitable. If on Earth, all of these environments would be inhabited. • Implication: Exploration of many sites (≥10 type environments) is necessary to search for life on ancient Mars and understand the environmental processes that controlled environmental habitability on Mars through time.

III. A Different, Distinctly Martian Paradigm for Life and Habitability

MRO's spatial resolution allowed geologic contacts between units of different composition to be discerned, relative stratigraphies to be defined, and ages to be determined. As the chronology became better defined, questions about the evolution of the physical environment to sustain Martian habitats for life became pressing and continue to be critical questions today.

> While it is commonly assumed there was some period of time in Mars history when all conditions favorable to habitability…existed simultaneously (active magnetic field, valley formation, erosion and transport, aqueous alteration, etc.)….a variety of observations constraining the timing of these processes suggests that it may not be the most probable scenario. –*Fassett & Head, 2011, Icarus [link]*

Mars appears to have remained habitable, at least from the perspective of available liquid water, even after we might expect. In other words, our current understanding of how planetary habitability responds to the evolution of solar luminosity and decrease in atmospheric pressure may be too conservative [see timeline in Ehlmann et al., 2016, *JGR*, Fig. 3]. Indeed, explorations by the Curiosity rover have shown a deep lake was present for at least thousands of years in Gale crater during the Hesperian period of Mars history[5]. Clearly, abiding questions remain about Mars' environmental evolution: was the early time period the warmest and wettest? In late lakes, did Mars at last achieve a climate optimum or was this a transient climate state?

Mars has characteristics affecting its astrobiological potential that are fundamentally different from Earth. Unlike Earth, Mars experiences large amplitude variations in its axial tilt (10° to 60°) [6] on 100 kyr to 1 Myr timescales that change the latitudinal distribution of insolation, the stability of the polar caps, and trigger atmospheric pressure increase and collapse. Thus, periodic massive climate change was a continual forcing function on the evolution of possible Martian life and the physical chemical reactions generating prebiotic molecules.

> Cold, arid conditions with only transient surface water may have characterized Mars's surface for over 4 billion years, since the early-Noachian period, and the longest-duration aqueous, potentially habitable environments may have been in the subsurface. -*Ehlmann et al., 2011, Nature*

In contrast to Earth's oceans, present continuously since >4 Ga, Mars likely had only episodic northern oceans fed by occasional outflow channel discharge[7]. Mars lost its surface radiation protection early (3.9-4.1 Ga) with the loss of a magnetic field; and the ~1 bar of atmospheric CO_2 modeled to be present[8] does not provide for mean surface temperatures above or near freezing. Much remains to be understood about Mars' early atmosphere. A basic disconnect exists between observations that demand rivers and lakes on the surface of Mars and climate models that suggest a cold Mars surface. Yet, very strong evidence exists at both the Opportunity and Curiosity landing sites for extensive groundwater aquifers in the past. While mineralogic evidence for water-rock interaction was widespread, geochemical evidence rarely shows the leaching expected in open system water-rock reactions[9]. This is distinctly different from Earth, where weathering driven by a surface hydrologic cycle delivered sediments to ocean basins for all of Earth history. Terrestrial shallow marine environments are sites of many of the early stromatolitic fossils, though others favor deep sea hydrothermal systems or continental playas as habitats for early life on Earth[10]. Thus, **Mars is both a challenge and an opportunity: to trace the evolution of a watery, but colder and less environmentally stable terrestrial planet through its first billion years and to explore for both surface and subsurface life**.

IV. The Most Pressing Questions & a Strategy for Exploration

The main exploration questions for Mars have transitioned from "Was Mars a habitable world?" (definitely, the answer is yes) to (a) "Was/is Mars inhabited?" and (b) "Why did major

[5] *Grotzinger et al., 2014, Science; 2015, Science*
[6] *Laskar et al., 2004, Icarus*
[7] *Tanaka et al., 1997, JGR; Pan et al., 2017, JGR; Wordsworth, Ann. Rev. EPS, 2016*
[8] *Acuna et al,1999,Science Kite et al, 2014, Nat.Geo..; Edwards & Ehlmann, 2015, Geol.; Hu et al, 2015, Nat Comm*
[9] *Taylor et al., 2010, Geology; Ehlmann et al., 2011, Nature*
[10] *Allwood et al., 2006, Nature; Martin et al., 2008, Nat. Rev. Microbio; Benner et al., 2008, AGU Fall Mtg.*

planetary-scale transitions in environmental conditions and habitability occur?" Regarding the latter, a 30+ author group of experts on terrestrial planet evolution recently wrote a review that detailed the key questions and required measurements [Ehlmann et al., 2016b]. The critical questions include understanding (1) Mars' environmental response to the decline of the magnetic field and the brightening of the early Sun, (2) what atmospheric composition and pressure permitted surface waters and how and why the atmosphere changed, and (3) the response of the Mars climate to periodic forcings from volcanism, impacts, and obliquity. Mars provides access to these early solar system and early planetary evolution processes with a geologic record far more pristine than that on Earth. In situ petrology, measurements of volatiles and noble gases, and chronological constraints at multiple locations and as a function of time are needed to understand the trends, rhythms, and local aberrations in Mars environmental history.

Why is this so pressing to the search for life in the universe? In the search for life, environmental 'snapshots' of rocky exoplanets will allow for ensemble statistics. The only way to discern the rules for stability (or not) of habitability over much longer timescales, and thereby understand the astrobiological potential of Earth-like worlds, is by solar system geologic records, particularly from Earth, Mars, and Venus. Mars stayed geologically active and intermittently habitable for at least 1.5 Gyr but was not so active that it overwrote its own history.

> The search for life on Mars must continue, but to maximize our chances of success, it needs to be informed by our evolving understanding of the early climate. –*Wordsworth, 2016, Ann. Rev. [link]*

The search for life drives astrobiology but there is a necessary scaffolding on which this search is conducted. As a result of Mars' distinctive diversity, exploration strategies that may be appropriate for other worlds will fail on Mars. In particular, no one landing site can be taken as representative of the whole planet and the whole planet's history. Life may have proliferated in many of the diverse habitable environments of early Mars. Or it may have been restricted to only a few or perhaps a single region. Perhaps life never evolved at all. Regardless of the answer, the conclusion is profound. Making this conclusion, however, requires a search in the rock record much like that conducted over the past decades that transformed our understanding of Archean and Hadean Earth. First, it is only by sub-meter and indeed sub-mm scale investigations of rock texture and composition that the suitability of the environmental conditions at a given site for biosignature preservation can be identified. Second, it is by studying the time-correlated history of the evolution of Mars that the fundamental physiochemical controls on the sustainability of habitability can be discerned. **The required measurements thus demand multiple site landed investigations with petrology, isotopic measurements, and age-dating or multi-site sample return.**

Due to a variety of programmatic, political, sociological, and technological factors, the recent trajectory of planned Mars exploration has not fully responded to the discoveries of the last decade of Mars' diversity. Single site sample return was prioritized at the expense of multiple site investigations. Mars sample return (MSR) has multiple longstanding, laudable scientific goals [e.g., see the e2e-iSAG report], would be a significant technological accomplishment, and would demonstrate capabilities needed for eventual human exploration. We agree with NASA AA Thomas Zurbuchen's comments in August 2016: doing MSR as quickly and inexpensively as possible, heavily leveraging international partners, would be a substantial accomplishment.

MSR would allow the search for life at one location on Mars and potentially, depending on the landing site chosen, the sampling of several different habitable environments on Mars. However, promotion of MSR as *primarily* a life detection mission is premature, given our current state of knowledge. We can and should search for life on Mars now[11] and in the past; indeed it is possible that Mars was widely inhabited and the conditions were nearly universally favorable for biosignature preservation. But our own experience from Earth's record suggests this perspective may be overly sanguine. If restricted to a single site, MSR is unlikely, alone, to answer the most fundamental astrobiological questions. This is particularly true for a negative result in life detection. To maximize our chance of success, diversity is needed.

By contrast, in the next 20 years, measurements from multiple sites could vastly expand our understanding of the early evolution of terrestrial planets and the fundamental controls on their astrobiological potential. Such measurements may even reveal life on Mars; they will at minimum convincingly identify the optimal places to look. While orbital data is essential to providing context and conducting surveys that identify targets of astrobiological importance, it is the diversity, mobility, and precision of in situ exploration that will further our understanding of the habitability of ancient Mars[12]. Diversity is needed to enable access to distinct type environments, and a combination of mobility and precision landing systems will maximize our ability to access the spatially continuous rock record in outcrops identified from orbit for measurement. The exploration of Mars for past habitability and biosignatures is only beginning.

Key Points	● To search for life and to reveal controls on terrestrial planet habitability through time, programmatic/mission systems approaches need to be developed to enable in situ investigation and/or sampling of at least a dozen type Mars environments. ● This could be achieved with multi-site sample return or multi-site in situ investigation with a capable payload. ● The critical measurements are (1) those that assess in situ petrology at sub-mm scale (texture+composition); (2) those that assess the isotopic composition of volatiles, noble gases, and organics trapped in rock; and (3) those that enable age dating to pin evolution of Martian processes in absolute time. ● These instrument types exist at TRL 6-9. The challenge is one of systems engineering to enable a multi-site approach within cost constraints. Continued miniaturization of payload instruments and payload systems, novel approaches to mobility (e.g., hoppers, helicopters), and novel approaches to landing that enable more rovers in smaller packages should be prioritized as science-enabling technologies.

[11] *see other white papers*

[12] *There remains ample work to do from orbit for understanding volatile reservoirs and the dynamic processes of modern Mars that feed understanding current habitability and the search for modern life [see NEX-SAG report].*

MARTIAN SUBSURFACE ICE SCIENCE INVESTIGATION WITH A SPECIAL REGIONS DRILL

A White Paper in response to the
ASTROBIOLOGY SCIENCE STRATEGY FOR THE SEARCH FOR LIFE IN THE UNIVERSE

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White Paper Description

Martian subsurface water ice, a likely abode for extant life, is a scientifically critical, untapped record that is expected to reveal major insights into processes and conditions that define Mars' system. In situ, robotic drilling into pristine subsurface ice will enable assessment of its native biological potential before human presence.

If life had evolved on early Mars, changes in the availability of liquid water and exposure to excessive amounts of ionizing radiation at the surface may have driven life to take refuge in the subsurface, where ionizing radiation levels were lower and more tolerable. Current model estimates for this "critical depth" (CD) are 1.5-2 m [1-2], but this value may change with ongoing research. Subsurface habitats at this depth could have persisted and evolved over millions to billions of years and could even exist today [3]. Deep subsurface ice (>5 m) may be a cryogenic vault for a dormant martian ecology, waiting for the next warming event (e.g., related to obliquity-cycle) to become mobilized in shallower, briny ground water. To date, the paucity of measurements of the martian subsurface environment, and absence of direct measurements of subsurface ice limits our understanding of its astrobiological status and potential.

Importantly, instruments on the Mars Reconnaissance Orbiter, Mars Express, and Mars Odyssey have revealed the presence of subsurface water ice within centimeters of the surface at higher latitudes (> 60° latitude) with an upper contact extending downwards and with some variability at lower latitudes [4]. Reanalysis of such data suggests near-surface ice present at a range of latitudes [5], though it is unclear how much is captured in hydrated minerals [6].

Investigation of subsurface environments is one obvious next step for Mars exploration and with it a prime science goal to search for signs of life, particularly extant life (or cryogenically, well-preserved ancient life). In situ science observations are necessary to assess the water ice for its potential biology, chemical composition, and past-present processes. To address the goal, knowledge of ice distribution at scales relevant to sampling and making measurements (mapped at 1-m or less resolution for ice that is accessible at depth) is required, together with chemical and physical context to support interpretations of signals and noise. Since signatures of terrestrial life can compromise the integrity of the mission, contamination control is paramount. As such, drilling must be robotic and humans must not be directly involved [7]. Lastly, it is expected that ice will be melted during drilling creating a "spacecraft-induced Special Region", thus from a planetary protection perspective, it will be a Special Regions drill and will come with physical, operational, planetary-protection, and cross-contamination issues and risks.

Drilling is a proven technology for accessing the subsurface. It enables access to and sampling of rocks, sediments, and ice at depth. Drilling on Mars supports investigations focused on astrobiology and the evolution of the martian climate[8]. Accessing samples below the critical depth allows for measurements of environments only minimally impacted by the radiation and aridity of the modern surface environment, allowing for the possibility of sampling organic material that has been better preserved since its deposition (if transported) or perhaps its formation (if subsurface life has existed). Measurements made at depth may reveal recent to modern near-surface processes responsible for altering the composition of surface materials and the atmosphere. Furthermore, geochemical and mineralogical measurements correlated with stratigraphic depth and/or geomorphological features (e.g. glaciers or impact structures) enables reconstruction of geological processes, past climate and elemental cycling through time.

Critical datasets to be acquired in the baseline science investigation must address the questions below. Such in situ data will support models.

Objective 1A: Does the water ice or pore water ice host extant life? If yes, is it dead, alive, or both? Addressing whether life is present or not requires an approach that instills a high level of confidence for interpretations. To do this, multiple and independent measurement types are needed to determine if signs of life are present. Each measurement capability must cover a broad range of signal strengths since the concentrations of biological materials is unknown. This top tier question requires tests for generic life features (e.g., amino acids complexity and chirality, lipid patterns and chain length distribution, molecular complexity, cell morphology/composition/activity). Samples for *in situ* measurements must include samples below tolerable radiation dose rates for Earth-like organisms I.e., the critical depth (CD). While there is no specific requirement for how samples are physically acquired, science integrity and planetary protection concerns require that absolute minimal contamination and alteration. As such, drilling is more controllable than excavation approaches, but coring is not necessitated by the science questions here, and may not be feasible if there is a mixture of rock and ice.

Objective 1B: If life is present, does it have Earth-like biochemistry? This objective 1B is secondary to 1A, but if there is indication of life, Obj. 1B is paramount for understanding evolutionary relationship with Earth life. Addressing this question requires tests for Earth-life-centric chemistry (e.g., nucleic acid- or antibody-based tests). Sequence-specific results for DNA/RNA might enable us to map martian life on the terrestrial tree-of-life and physiological (spore-formers?), metabolic, and biochemical details. If DNA or RNA are not detected, then results guide further exploration. As with Obj. 1A, multiple and independent measurement types are needed to build confidence in interpretations and rule out false negative results.

Objective 2: What is the general oxidant chemistry and its distribution with depth? Oxidants (e.g. perchlorate, chlorate, peroxide, and oxalate, which are all plausible as constituents in the water due to primary or secondary formation from radiation exposure at or near the surface [9-10]) may be energy sources for life, waster products, or poisons. Their abundance may shed light on habitability, organic preservation potential, and subsurface transport.

Objective 3: What is the general organic chemistry and its distribution with depth? Dissolved and volatile organics in ice are fundamentally part of a potential ecosystem as they may represent both food and waste products of organisms (e.g. CH_4, acetate) – or poisons (e.g. HCN). It is unclear what subsurface processes alter organics and their long-term preservation.

Objective 4: What is the general solution chemistry and its distribution with depth? Key measurements are: Cl^-, Br^-, I^-, ClO^-, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^+, K^+, salinity, pH, Eh, δH, and $\delta^{18}O$. The results offer essential context for Obj. 1A-B interpretations, will help piece together the ice deposit origin and history, constrain key habitability parameters, and may shed light on organic preservation potential and subsurface processing.

Objective 5: What other chemistry of the subsurface ice environment might strongly influence habitability? Subsurface nutrient availability is key context for understanding biological potential (presence/absences and activity). CHNOPS elements are known to be present in martian soils and ancient sediments in biologically accessible forms [11-12]. Bioavailable forms of CHNOPS and metal ions (nutrients or poisons) may vary in composition and distribution.

Objective 6: Radioactive isotopes? Radionuclides in the subsurface ice and particulates may be native to the deposit or generated by cosmic radiation [13]. Radio-decay from subsurface materials probably has little influence on habitability, but observations of radionuclide decay (noble gas or other) can be a powerful tool in dating host sediments and processes occurring in subsurface ice (e.g. [14]), which may be critical context for understanding possible habitats.

The threshold science is minimal version science objectives and capabilities that still warrant the investigation/mission. In this case, the threshold science investigation must establish confidence in the potential for the presence of life. Objectives 1A, 2, 4, and salinity, pH, and Eh measurements only of objective 3 compose the threshold investigation.

DRILLING

The probability of not reaching ice, in an investigation that critically depends on doing so, is a mission-critical risk; however, *a priori* detailed (orbital or ground; ≤1-m resolution) knowledge of the locations to be drilled will significantly help mitigate the risk of a dry hole. The simplest achievable way to manage the dry-hole risk is to go where subsurface ice to known to exist below the critical depth, e.g., high latitude sites. Otherwise, local survey before drilling are needed. Such a survey could be accomplished by: (a) making measurements from another landed Mars mission, (b) putting the drilling and sample analysis instruments on a mobile platform together with the local-survey instruments (GPR, seismic) that could provide guidance to locations where near-surface ice was detected, or the cost-effective, preferred option (c) using two platforms that operated in tandem. In the latter scenario, a small "ice prospecting rover" would locate drill targets, image and retrieve ice-bearing samples, then take them to a "lab lander" platform where processing and detailed analysis would be completed.

How many holes and samples per hole define our threshold and baseline investigations? How much heterogeneity do we expect local conditions to reflect in terms of ice patchiness laterally and with depth? Assuming that we require either multiple landing sites and/or mobility within a given landing area, to reduce the risk of a dry hole, then we may trade against the various mission architectures for subsurface ice access, considering which would give us the best amelioration of these risks. A threshold science mission could be composed of as little as 2 drill holes (must not be dry holes) that each penetrate below the CD, within the same location for corroborative observations, and with 5-6 samples (~0.5-m apart; number depending on total drill depth). At least one sample per hole must be from below the CD. A baseline mission may include capabilities for deeper drilling and more holes and more samples per hole to support statistical analyses and contamination monitoring.

Generations of drill prototypes have been field tested. Most are externally augered and readily cleanable. Current capabilities support drilling 1 m into ice, ice-cemented soil or dry rocky material at the mid-latitudes on Mars at a rate of one to several hours per meter, depending on the substrate. A threshold mission that only drills two holes total is not ambitious and satisfies threshold science as long as the holes contain ice for analyses. Further, a mobile platform will not be overly time constrained by drilling to >2 m, but given multi-sol activities, an ice-prospecting rover will require onboard storage for these powdered samples (volatiles and ices), so they do not sublimate before they can be returned to the lab lander for processing.

PLANETARY PROTECTION CONCERNS

Independent of the exploration approach (a-c), planetary protection concerns will need to be addressed. Even if the formal parameters described in COSPAR planetary protection policy for defining a Special Region are not present naturally (A_w>0.5 and T>255K, concurrently), the action of drilling will likely cause transient excursions above these limits, which would impose a planetary protection category IVc mission requirements (cf. Phoenix). Additionally, the intent to perform life signature analyses on samples from the borehole would potentially lead to classification as a life-detection (planetary protection category IVb) mission (cf. ExoMars 2020). The constraint to clean the sample handling chain from contamination would likely drive the need for microbial bioburden reduction of that hardware, and potential life signatures (“dead bug bodies”) removal too, together with a requirement for recontamination prevention until deployment at the research site, the ice prospecting rover and its drill system could be designed to be robust to undergoing a microbial bioburden reduction process as a single unit, with only the sample handling chain of the analytical instruments being so processed, ensuring both the scientific integrity of the sample and the protection of the martian environment from release of viable terrestrial microbes. This approach implies the need for biobarrier technologies, as were used for both Phoenix and Viking, which must be included in the design activity.

SCIENTIFIC INTEGRITY AND CLEANLINESS

Independent of planetary protection requirements, to achieve the highest sensitivity in a life signature measurements, the drill hardware would need to be cleaner than required for (forward) planetary protection purposes. For this reason, the authors considered the potential for a “two-string” cleaning/sterilization process: the concept is for pre-launch cleaning to the appropriate level (driven by the detection limit for the analysis) and then protection against recontamination, with the “second string” being a “point of use” decontamination step. This second decontamination step would allow for recovery from post-launch contamination events (nominal and off-nominal) to ensure that at the point in time when the drilling activity is performed, the drill hardware is clean-enough to obtain a pristine sample.

For a life signature detection, it is clear that cleaning processes resulting in killing live organisms and leaving their carcasses behind is inadequate, however monitoring for contaminant presence may well end up essentially duplicating the life detection capability of the instrument. It is expected that confirmation of a signal will rely on other approaches rather than contamination monitoring alone, in particular: 1) making multiple measurements, 2) extensive use of blanks, and 3) use of corroborating data from instruments making orthogonal measurements.

KEY AREAS OF RISK REDUCTION AND NEXT STEPS

Key areas of risk reduction include technology development and demonstration of mobilized >2 m drilling with point-of-use decontamination of the drill auger as well as a cache and deliver approach that maintains sample integrity for priority science measurements. Both aspects must be included in the spacecraft and in the operational design of a mission. In addition, capabilities of a laboratory platform to accept, process (filter? dilute? concentrate?), and portion samples to science instruments while managing sample-to-sample contamination need to be developed. Sample-processing-subsystem development would strongly benefit from an integrated instrument package with pre-determined sampling requirements. Development of novel contamination control approaches amenable to deployed technologies will enable life detection missions. Lastly, and to re-iterating the high risk imposed by possible dry holes, high-resolution mapping of near-surface, drill-accessible water ice (abundance and distribution) are needed. Remote observations that expand on current data would vastly support risk mitigation as a next step, particularly regarding any seasonal variation that may occur.

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Planetary Protection should enable the exploration of Mars and not prohibit it

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Planetary Protection should enable the exploration of Mars and not prohibit it

Introduction

The title of this white paper is a direct quote from the first page of the COSPAR document "Proposed new terms of reference for the COSPAR Panel on Planetary Protection", presented at the COSPAR meeting in Paris, France, 2017, and approved by the COSPAR Bureau on March 22, 2017. We enthusiastically endorse this sentence. And we suggest that the current *NAS Study of the state of the science of Astrobiology as it relates to the search for life in the Solar System*, as well as the upcoming *Decadal survey in Planetary Science*, should both include a discussion about the effects that the strict application of Planetary Protection policies is having on the astrobiological exploration of Mars, which is resulting in a continued delay in the search for Martian life.

Statement of the problem

Current Planetary Protection policies demand that strict planetary protection measures should be applied before sampling regions on Mars which could be a habitat for certain types of microorganisms, either native from Mars or brought there from Earth. Otherwise, the argument is that (1) terrestrial biological contamination could jeopardize a possible extant martian biosphere, and (2) it might be difficult to distinguish between any indigenous Martian life forms and life that arrived as contamination from Earth in our spacecraft.

We disagree with this fearful vision. The main point we make in three recent publications (Fairén and Schulze-Makuch, 2013; Fairén et al., 2017, 2018) is that we're being overprotective of Mars. There are several reasons why this situation needs to change, so we can resume a true biological exploration of Mars right away. Succinctly, these reasons are:

1. Mars is likely already contaminated with terrestrial (micro)organisms carried by dozens of unsterilized or poorly sterilized spacecraft sent from Earth in the last decades, and by common asteroid exchange. If Earth life cannot survive and most importantly reproduce on Mars today, our concerns about forward contamination of Mars with terrestrial organisms are unwarranted; on the other hand, if Earth microorganisms can, in fact, survive and create active microbial ecosystems on present day Mars, we can presume that they are already there (Fairén and Schulze-Makuch, 2013).

2. Any indigenous life on Mars should be much more adapted to Martian stresses than Earth life is, and therefore would outcompete any possible terrestrial newcomers. For example, it has been argued that the salinity of surface waters on Mars usually exceeded levels tolerated by most terrestrial organisms (Tosca et al., 2008). However, we know that a significant number of microorganisms on Earth thrive exclusively in places with inherently very high salinity (such as some lakes in

Antarctica or salt crusts in the Atacama Desert, e.g. Rothschild and Mancinelli, 2001), similar to that estimated for ancient water solutions on Mars. Therefore, we can imagine that any potential Martian biosphere would have been subjected to an enormous evolutionary pressure during billions of years to become specialized in inhabiting extremely salty environments; and the same argument would be applicable for the adaptation of the Martian organisms to radiation, oxidative environments and any other stresses common on the Mars surface. The microorganisms hitchhiking on our spacecraft would probably not be able to compete against these super-specialized Martian organisms in their own territory.

3. Sterilization methods applied to our spacecraft don't actually "sterilize" them, as we still don't know how to accomplish real sterilization (Nicholson et al., 2009): we just thoroughly clean our robots, killing only those microorganisms with no chance of surviving on Mars anyway. This is because the cleaning procedures rely basically on the same stresses prevailing on the Martian surface, such as oxidizing chemicals and radiation. Therefore, current cleaning protocols are essentially conducting an artificial selection experiment, with the result that we carry to Mars only the really hardy microorganisms with some characteristics that might allow them to survive on Mars. This should put into question the whole cleaning procedure.

4. Following the previous argument, the current robotic exploration of Mars will have little (if any) impact on potential Mars biospheres or on our efforts for searching for active life on Mars. After the interplanetary trip and just a few days on Mars, our rovers and landers will be as biologically clean (and maybe even more) as the Viking probes were when they left Earth (Khodadad et al., 2017). Therefore, MER- and MSL-like cleanliness levels should be sufficient to allow a robot to search for life on Mars.

5. Technology has advanced enough that distinguishing between Earth organisms and Martian organisms is no longer a problem (assuming that some Earth microbes could still get to and survive on Mars, which is very doubtful after the previous arguments). If Martian life is biochemically similar to Earth life, we could add Martian life to the tree of DNA-based life that we already know, probably somewhere on its lower branches; and if it is different, we would be able to identify such differences based on its building blocks (Fairén et al., 2017). In addition, we can distinguish between Mars and Earth life because we can identify and control the diversity and quantity of microbial populations in our clean rooms, and therefore the microorganisms potentially travelling in our spacecraft can be recognized (van Heereveld et al., 2016).

6. Given NASA’s (and other agencies as well as the private sector) hope to send human missions to Mars in the 2030’s, current planetary protection guidelines applied to today’s unmanned robots are impractical: humans would inevitably bring microbial hitchhikers with them very soon, because we cannot sterilize humans. Some degree of forward contamination associated with human astronaut explorers is inevitable (Conley and Rummel, 2010), as it will be impossible for all human-associated processes and operations to be conducted within entirely closed systems (Rummel et al., 2014). Therefore, continuing delaying the robotic astrobiological exploration of Mars because we don’t want to contaminate the planet now with microorganisms hiding in our spacecraft is not reasonable.

7. Shouldn’t we find out prior to sample return missions and human landings whether there is indigenous life on Mars? The answer is yes, please: we need to have a better idea whether there is life on Mars or not, and what robots or astronauts might find there and/or bring back to Earth. Doing so, we will contribute to increasing the safety of Earth´s biosphere. After all, we still don’t know if returning samples could endanger humanity and the terrestrial biosphere if there is life on Mars.

Suggested solutions to be discussed in the NAS Astrobiology science strategy for the search for life in the universe

Worries of contaminating Mars with Earth microorganisms have delayed sine die a thorough astrobiological exploration of the planet. As a result, since Viking no other Mars mission carried true life-detection instrumentation. We advocate here for a sharp change of direction in the exploration of Mars, to be included in the *NAS Study of the state of the science of Astrobiology as it relates to the search for life in the Solar System* and to be discussed in the upcoming *Decadal survey in Planetary Science*. The change of strategy we propose is twofold:

- Firstly, allowing immediate access to the Special Regions for vehicles with the cleanliness level of Curiosity, Mars2020 or ExoMars. Special Regions could hold a sluggish extant biosphere able to reproduce biomarkers even under current Martian radiation, while biomarkers of extinct life would simply degrade in several hundred millions of years in the top meter of Martian surface due to exposure to cosmic rays (Pavlov et al., 2012) and the oxidizing surface chemistry (Mancinelli, 2017). Therefore, the focus on detection of evidence for extant life in surface rocks and regolith at Special Regions is actually more realistic than the hopes to detect ancient organic biomarkers at or near the Martian surface on the long timescale. To allow spacecraft access to Special Regions, it would be necessary to reevaluate the current Planetary Protection restrictions and make sure they are properly adapted for the new space age we are entering, particularly distinguishing clearly between spacecraft cleanliness for biological reconnaissance and spacecraft cleanliness for planetary protection. This will reduce the likelihood that spacecraft cleanliness issues create again conflicts between planetary protection efforts and science objectives. These proposed changes would require that COSPAR update the rules governing the robotic exploration of Mars, and the United Nations Outer Space Treaty should be amended as well, although in fact Article IX in the Treaty is very vague, and crucially "harmful" is not defined (UN Treaty).

- Secondly, we urge that our existing laboratory robotic technology is made flight ready in the search for biochemical evidence of life (e.g., McKay et al., 2013), and in particular, we advocate the development of robotic tools for the characterization of organic compounds as unequivocal signs of life. Arguably, the characterization of complex organic chemistry should be the relevant astrobiology science at this point for Mars. The organic characterization should be adequate to determine if the organics recently found on Mars (Freissinet et al., 2015) result from biological processes rather than being part of the abiotic organics that are ubiquitous in the Solar System. Natural selection has resulted in life on Earth specializing in the use of certain organic molecules in the construction of biomass. The basics for life on Earth is the 20 L amino acids, the pyrimidines (U,T,C) and purines (A,G), the D sugars, and a few lipids. A collection of similar (not necessarily the same) basics is likely to be common to any life form that has developed by natural selection. Hence one way to determine if a collection of organic material is of biological origin, is to look for a selective pattern of organic molecules similar to, but not necessarily identical with, the selective pattern of biochemistry in life on Earth. Implementing this search in practical terms in near term missions will require a sophisticated ability to separate and characterize organic molecules. Currently the instrument best suited for this task is a GCMS with solvent extraction. However, new methods of fluorescence and Raman spectroscopy could provide similar information and may have a role in future mission applications. We will need also nucleic acid sequencing instrumentations for future in-situ detection and/or sample return (Carr et al., 2017), and parallel analyses for complex and polymeric sugars, lipids, peptides, and nucleic acids, as well as their building blocks such as sugars, nucleobases, and amino acids, so we will no longer be concerned about possible false positive life detection. Robotic microscopes with very high resolution to analyze samples could also help to identify different cellular architectures.

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LIFE-DETECTION TECHNOLOGIES FOR THE NEXT TWO DECADES

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1. LIFE-DETECTION: A CENTRAL RATIONALE FOR SPACE EXPLORATION

Since its inception six decades ago, astrobiology has diversified immensely to encompass several scientific questions including the origin and evolution of Terran life, the organic chemical composition of extraterrestrial objects, and the concept of habitability, among others. The detection of life beyond Earth forms the main goal of astrobiology, and a significant one for space exploration in general. This goal has galvanized and connected with other critical areas of investigation such as the analysis of meteorites and early Earth geological and biological systems, materials gathered by sample-return space missions, laboratory and computer simulations of extraterrestrial and early Earth environmental chemistry, astronomical remote sensing, and in-situ space exploration missions. Lately, scattered efforts are being undertaken towards the R&D of the novel and as-yet-space-unproven ‘life-detection’ technologies capable of obtaining unambiguous evidence of extraterrestrial life, even if it is significantly different from Terran life [1]. As the suite of space-proven payloads improves in breadth and sensitivity, this is an apt time to examine the progress and future of life-detection technologies.

2. ELSI-EON WORKSHOP ON LIFE DETECTION TECHNOLOGIES

The past four National Aeronautics and Space Administration (NASA) Astrobiology Roadmap documents acknowledged the need to develop technologies that can unambiguously detect life on habitable planetary bodies [2]. These roadmaps also mention the importance of assessing habitability and biosignature preservation potential, searching for liquid water, and defining thermodynamic constraints as critical parameters for selecting planetary targets and sites for future life-detection missions.

The Earth-Life Science Institute (ELSI) is a vital research center for trans-disciplinary scientists across the world working towards the grand scientific questions of understanding the formation of the Earth, the origins of life, and the evolution of inhabited and habitable objects in the solar system and elsewhere in the universe. An international workshop entitled “Life Detection Technology: For Mars, Enceladus, and Beyond” was organized on October 5-6, 2017 at ELSI; the co-authors of this white paper were the participants. The purpose of the workshop was to **(a)** deliberate the utilities of diverse life-detection payloads on space probes for exploring planetary bodies in the solar system with dissimilar habitability potential; **(b)** cultivate international synergies between scientific and engineering laboratories from around the world for efficient R&D of life-detection technologies; and **(c)** add to the transdisciplinarity of this domain by bringing in new scientific and engineering disciplines that are presently outside astrobiology and could assist in the development of life-detection technologies. This white paper summarizes the discussions that emerged from this workshop, which included participants from France, Germany, India, Japan and the United States. The participants presented their perspectives on what might constitute a signature of life, and what technologies might enable such detection.

Among the leading questions in astrobiology are: What is life? How do we define life? Will life elsewhere be identical or similar to Terran life? And what planetary environmental parameters determine habitability? These are presently studied from various physical, chemical, and biological perspectives [3]. Since these are grand scientific questions, they are difficult to tackle from the narrow purview of stove-piped scientific disciplines. Astrobiology and instrument-driven life detection stimulate transdisciplinarity, to which the congregation of this workshop was testament. The emergence of technical capacities to explore the surfaces of planetary bodies through space probes, e.g., landers, rovers and orbiters, are revitalizing the possibility of answering these questions. The space agencies in the United States, Japan, India, and the European Union pursue the R&D of space payloads dedicated to the search of bio-geo-chemo-signatures. However, presently none of these payloads are capable of detecting life. As life-detection technologies become increasingly central for in-situ explorations, they will significantly advance our scientific understanding of the possibilities of life to survive beyond Earth, even simultaneously on multiple celestial objects. Therefore, apart from the basic scientific research, it is also essential to contemplate the technical demands of life-detection. The deliberations from this workshop are succinctly presented in the following sections.

3. HABITABILITY ON PLANETARY AND NICHE SCALES

The habitability of any planet or satellite is estimated from its size, surface composition, climate, orbit, and exposure to stellar radiation, among other parameters. Prior knowledge of the events that each planetary body experiences during its formation is also imperative. For example, events such as bolide impact-driven degassing of volatiles from planetary interiors may result in rapid retention of liquid water on the planetary surface and a gaseous atmosphere. With the advent of next-generation astronomical observatories like the James Webb Space Telescope, the Extremely Large Telescope, and the Wide Field Infrared Survey Telescope, the theoretical knowledge of planetary habitability will receive support from a sizeable statistical set of spectrally-characterized extrasolar planets. A reasonably-sized sample set of extrasolar planets will potentially contribute to our understanding of the possibility (or possible forms) of life existing on them. The telescopes and other instruments used for the characterization of habitable extrasolar planets will also characterize habitable bodies in the solar system at much higher spatial resolutions. These intra-solar system observations will be necessary for selecting landing site, a crucial factor shaping the type of life-detection payloads aboard exploration probes.

Lessons from the traditional laboratory-based prebiotic chemistry research can tentatively inform the search for potential extraterrestrial biosignatures, but reliance on these studies to determine reasonable biomarkers must be considered critically. Extant biochemistry is presumably a product of the molecular evolution of various chemical species that might have populated the prebiotic soup. This process was perhaps driven by pertinent selection pressures across millennia, which eventually resulted in life as we know it today. Present prebiotic chemistry research is heavily biased by our knowledge of extant biochemistry. It is vital to acknowledge that “acceptable” biosignatures could be biopolymers that have never been achieved in prebiotic chemistry research, not to mention that chemistries in the sterile, controlled laboratory may be very different from chemistries in the field. A complete bias towards finding extant Terran biosignatures when searching for life elsewhere should, therefore, be avoided.

It is supposed that the most convincing biosignatures are likely to be organic, simply because carbon is uniquely able to form a vast structural and informational molecular repertoire. Life-detection techniques targeting a wide array of carbon-based molecules can be applied to all samples, those existing in the same or different environments or even environments undergoing temporal variation. The insights obtained from such an approach is that extant biological, abiological or extinct biological samples will all provide unique identifiable signals. Biological and abiological samples may both contain thousands or millions of unique low molecular mass chemical species, and these can be explored in depth in the laboratory. Even if the identities of these species are not entirely known, the relationships between them can be indicative of biology. This aspect could be especially useful for extraterrestrial life-detection, as it is possible the nature of terrestrial biochemistry is either historically contingent or tightly linked to Earth’s geochemistry, and thus alien life could have evolved differently. Terran life produces a unique ensemble of organic molecules that is distinct from the vast combinatorial chemical space of abiotic chemistry. To maximize the chances of identifying real biosignatures and avoid false positives, an approach targeting chemical distributions to identify patterns unique to life will be necessary.

4. CONCEPTS & TECHNOLOGIES UNDER CONSIDERATION

Life-detection demands a technologically intricate space mission design. One causal factor of this intricacy is the fact that habitable environments are not distributed globally on planetary bodies, but possibly exist in geographically limiting niches. Reaching such often-inaccessible sites will require agile robotic probes that are robust, able to seamlessly communicate with orbiters and deep space communications networks, be operationally semi-autonomous, have high-performance energy supplies, and are sterilizable to avoid forward contamination. Moreover, to build confidence in any positive detection of life beyond Earth, cutting-edge payloads are needed that can investigate multiple aspects of the 'Life Detection Ladder' described previously [4].

Despite their potential habitability, the environmental conditions on Enceladus, Mars, and other planetary bodies are dissimilar to Earth and hence pose challenges for the R&D of appropriate life-detection instruments. Even assuming that life could exist in all these places, the workshop participants noted that a probe-payload combination designed for a mission to a potentially habitable niche on one planetary body would not work seamlessly for niches on another body. Given the distinct biology or bio-chemo-markers that different environments sustain, thus the probe-payload combination and the space mission design needed to explore habitable zones on Mars, Enceladus, Titan, and Europa would need to be custom-made.

In agreement with the suggestions of the NASA Life Detection Ladder, the participants in this workshop promoted a variety of life-detection instruments. In-situ visual recognition of micro-organisms and detection of genetic or metabolic bio-macromolecules are some of the current aims of extant life detection technologies. The bio-geo-chemo-signatures of extinct and extant life can be detected using Raman and other spectroscopy techniques, enantioselective and two-dimensional gas chromatography, high-resolution mass spectrometry, microfluidic devices, and microscopes. The workshop participants agreed on the necessity to pursue life-detection space missions with a suite of several instruments. Results obtained from various instruments can avoid spurious measurements and provide statistical analysis.

To search for life in regions theoretically devoid of life requires novel detection techniques or probes. For example, air sampling in Earth's stratosphere with a novel scientific cryogenic payload has led to the isolation and identification of several new species of bacteria; this was an innovative technique analyzing a region of the atmosphere that was initially believed to be devoid of life [5]. Novel high-sensitivity fluorescence microscopy techniques may be utilized to detect extraterrestrial organic compounds with catalytic activity surrounded by membranes, i.e., extraterrestrial cells [6]. Nucleic acid (i.e., genetic/informational biopolymers) detection and sequencing [7] provides an even more unambiguous approach to detecting ancestrally related life, Terran contamination, or non-familiar nucleic acid-based life. Despite the advent of highly portable single-molecule sequencing technology, current methods require extensive conditioning of nucleic acid molecules (library preparation) and biological reagents. Technologies under development, such as quantum tunneling-based nanogap devices [8], could eliminate this complexity and simultaneously target nucleic acids, peptides, and other small molecules while achieving improved detection limits and broadening the potential range of life that could be detected. Incorporating microfluidics—due to their requirement of small fluid volumes, miniaturization, and low power consumption—that use novel nanomaterials for identifying microorganisms or their signature molecules is an ideal proposition for space missions which have weight and size constraints. Enantioselective separation techniques can distinguish between amino acids and sugars formed by abiotic or biotic reaction mechanisms and detect molecular homochirality, which may be a diagnostic biosignature [9]. Enantioselective gas chromatography has been utilized on the ESA Rosetta and ExoMars and NASA Mars Science Laboratory missions. It can be used with pertinent innovation for future life-detection missions.

Mass spectrometry (MS) has been extensively used for surface and atmospheric chemical characterization on numerous space missions. Miniaturized mass spectrometers with increased mass resolution and multiple steps of fragmentation (e.g., Cosmo-Orbitrap by European Space Agency (ESA), MULTUM by Japan Aerospace Exploration Agency (JAXA), and MASPEX and LD-TOF-MS by NASA) will be available for in-situ measurements on future life-detection missions. These MS techniques would allow characterization of high-mass organic solids including biopolymers and also enable in-situ elemental composition measurement for mineralogy and isotopic dating methods [10], which are essential for characterizing geo-chemo-signatures of habitability. The exciting developments in machine learning and its application to complex MS data will be invaluable in aiding the detection of organic and inorganic markers of biology. The specificity of these and other instruments also suggest life-detection missions demands the continuous invention of novel probe-payload combinations customized for exploration of each potentially habitable site. In the 2020s, sample-return missions like JAXA's Martian Moons eXploration mission to Phobos and Hayabusa-2 to asteroid Ryugu and NASA's OSIRIS-rEX to asteroid Bennu will refurbish the Earth-based infrastructure for environmentally-controlled and near-sterile curation and analyses of organic-enriched extraterrestrial materials. The sample handling knowledge generated from these missions will improve planetary protection procedures. Along with the advances anticipated from in-situ exploration, sample-return missions will also contribute to advances in handling potentially biotic extraterrestrial materials.

Sample-return missions are inherently technically sophisticated, but high-performance ground-based instruments can extensively characterize returned samples. High-resolution analyses on in-situ exploration missions are presently challenging from the purview of data transmission rate, as huge amounts of data may be generated. These aspects of life-detection missions call for the advancement of the current deep space communication technologies.

Analytical instruments associated with high-powered synchrotron radiation and magnetic field facilities will continue to possess superior characterization abilities, and only through sample-return missions, their features could be utilized. Ultra-high resolution Fourier-transform-ion cyclotron resonance-MS supported by high magnetic fields allows unambiguous assignment of molecular formulas to samples containing high molecular mass organic solids and polymers. Another technique, the synchrotron-based scanning transmission x-ray absorption microscopy is capable of distinguishing the distributions of protein, polysaccharide, and lipid in a living microorganism, and also characterizing biomineralization and nano-scale bioweathering. These techniques are disposed to provide more reliable and comprehensive characterization of chemically-complex materials. Efforts are also being undertaken to process high-resolution chemical characterization data with pattern recognition, machine learning, and artificial intelligence to determine the biological or abiological origin of the samples, a crucial determinant of the presence of life.

5. CONCLUSION

The authors of this white paper unanimously recognize the significance of life-detection instruments for unambiguous identification of extraterrestrial life and addressing the challenges involved in this. The authors acknowledge the necessity to establish an international network to forge collaborative R&D of life-detection technologies and a worldwide peer-reviewing network for data analyses. Life-detection is a capital-intensive endeavor capable of yielding enormous scientific return-on-investment and industrial spin-offs. An international network is crucial for pooling and coordinating human, financial, and technical resources and harnessing creativity, talent, and infrastructure across institutions and governments. These factors will be vital for the R&D of life detection technologies and the growth of astrobiology as a science in the decades to come.

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On the Past, Present, and Future Role of Biology in NASA's Exploration of our Solar System

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Humanity has been exploring our solar system with robotic spacecraft for just over 55 years (Mariner 2, launched in August of 1962, made the first planetary flyby – of Venus – in December of that year). In the years and decades since, planetary science and astrobiology have grown and expanded, both in terms of exploration targets and science questions. Here we provide a brief, but hopefully useful, perspective on the role of biology in NASA's planetary science goals and spacecraft missions, past, present, and future. We argue that while biology – via astrobiology – generates much interest and excitement for NASA, biology is vastly under-represented as a science within NASA missions.

While astrobiology and planetary science can and should be seen as distinct, they clearly overlap and there is often confusion as to where one ends and the other begins. Definitions for planetary science are varied, but usually reflect its multidisciplinary nature. The 2011 Vision and Voyages Decadal Survey for Solar System Exploration ((Space Studies Board (2011), hereafter denoted by VV2011) focused on planetary science and defined it, and we therefore use that framework for addressing the role of biology in solar system exploration.

In VV2011 the following definition was put forth: "*Planetary science is shorthand for the broad* ***array of scientific disciplines*** *that collectively seek answers to basic questions such as* ***how do planets form, how do they work, and why is at least one planet the abode of life****. These basic motivations explain why planetary science is an important undertaking, worthy of public support.*" Here the boldface is ours and is used to draw attention to two key aspects of this definition. While the 'array of scientific disciplines' is never defined, one could argue that the most basic disciplines from which to form an array would be: physics, chemistry, geology, and biology. In addition, the second bolded clause specifically implicates biology as one of the necessary disciplines in the array, since surely biology would be important when seeking answers to the question of 'why is at least one planet the abode of life'.

After defining 'planetary science', VV2011 then proceeds to argue for programmatic balance across mission types – Discovery, New Frontier, and Flagship (please see page S-5 of VV2011 for detail). While programmatic balance sounds good and is useful from a cost and implementation perspective, such balance explicitly does not consider the array of scientific disciplines previously defined and how they interact with different mission types. In doing so, this sort of architecture-based balance inadvertently marginalizes biology and its role in missions.

If we consider the array of disciplines that comprise planetary science, and examine their role throughout NASA's history of planetary exploration missions, we find the following:

	Pioneer 10	Pioneer 11	Voyager 1	Voyager 2	Viking 1	Viking 2	Galileo	……..	Cassini	GRAIL	MSL	MESSENGER	Dawn	New Horizons	Juno	Insight	OSIRIS-REx	Lucy	Psyche	Mars 2020	Europa Clipper
Physics	X	X	X	X	X	X	X		X	X		X		X	X	X		X	X		X
Geology			X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	X	X
Chemistry			X	X	X	X	X		X		X	X	X	X	X		X			X	X
Biology					X	X														/	

Please note that this is not a comprehensive list of every mission (as indicated by the ellipses), and that this assessment is strictly in the judgement of the authors of this whitepaper. As can be seen in the matrix above, the disciplines of physics, chemistry, and geology have been well served by NASA's current exploration and science strategy. Biology, however, is not well-represented. If we examine the programmatic balance aspect of mission types, we see that this difference is further exacerbated, as biology has really only played a role in a few Flagship-class missions.

Discovery Missions

	CONTOUR	Genesis	Lunar Prospector	NEAR	Mars Pathfinder	Moon Mineralogy Mapper	Kepler	Stardust	GRAIL	Deep Impact	MESSENGER	Dawn	Insight	Lucy	Psyche
Physics	X	X	X	X			X	X	X		X		X	X	X
Geology	X		X	X	X	X			X	X	X	X	X	X	X
Chemistry		X				X		X		X	/	X			
Biology															

New Frontiers Missions

	New Horizons	Juno	OSIRIS-REx
Physics	X	X	
Geology	X		X
Chemistry	X	X	X
Biology			

Flagship Missions

	Voyager 1	Voyager 2	Viking 1	Viking 2	Galileo	Cassini	MSL	Mars 2020	Europa Clipper
Physics	X	X	X	X	X	X	X	X	X
Geology	X	X	X	X	X	X	X	X	X
Chemistry	X	X	X	X	X	X	X	X	X
Biology			X	X				/	

Obviously, part of the explanation for this is that a certain level of 'scientific reconnaissance' needs to occur before we understand whether or not biology questions could be applicable to any given target. This makes sense for the initial stages of our robotic exploration of the solar system, as the physics, chemistry, and geology of a world lay the foundation for life's origins and planetary habitability. Moving forward, however, we argue that biology should play an ever-increasing role in our exploration strategy.

Biology as a science has experienced tremendous advances since that first launch of Mariner 2 in 1962. The discovery of DNA was still fresh while Mariner sat on the launch pad, and that discovery would give rise to PCR and other genetic and proteomic techniques that would revolutionize our understanding of life on Earth. The Viking Lander payload was designed based on our best views of life at the time, in the 1970s, but great discoveries such as Archaea, hydrothermal vents, and cryptoendoliths in Antarctica all occurred after our efforts to search for signs of life on Mars with the Viking spacecraft. In the decades since, we have also greatly advanced our understanding of biology's fingerprint in ancient rocks on Earth, and what measurements (and measurement combinations) are needed to provide a robust approach to seeking signs of life – whether it be in ancient rocks on Earth or in rocks or ices on distant worlds.

The science of biology is ready to extend beyond Earth through the launch and operation of missions that could seek out and discover potential biosignatures. For the first time in the history of humanity we have the tools and technology capable of directly measuring signs of life on other worlds. Through our past exploration we have come to learn and appreciate that physics, chemistry, and geology all *work* beyond Earth…but we have yet to make that leap for *biology*. Does biology *work* beyond Earth? Our path forward for solar system exploration could answer that question within the next 15 to 20 years, if NASA truly commits to that goal.

In summary, we suggest that future missions to solar system targets such as Europa, Mars, and beyond consider not just programmatic balance in terms of distribution of missions across solar system bodies and amongst mission categories, but also overall scientific balance in terms of how each potential mission helps to extend our fundamental understanding of all of the scientific disciplines that make up planetary science. We have reached a crossroads where we now have the opportunity to study the solar system through a biological lens, and we urge NASA and the scientific community to consider biology as one of the fundamental criteria against which mission relevance is judged.

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Astrobiological Potential of the Europa Lander Mission Concept

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Overview

Jupiter's moon Europa is a prime target in our exploration of potentially habitable worlds beyond Earth. Europa, which is approximately the size of Earth's moon, very likely harbors a global, ~100 km deep, liquid water ocean beneath its relatively thin (<25 km) ice shell. This ocean exists today and it has possibly persisted for much of the history of the solar system. Europa's ocean is probably in contact with a rocky, silicate seafloor, which may lead to an ocean rich in the elements and energy needed for the emergence of life, and for potentially sustaining life through time. **Europa may hold the clues to one of NASA's long-standing goals – to determine whether or not we are alone in the universe.** NASA is currently studying an astrobiology-focused Europa Lander mission concept. **The highest-level science goal of the Europa Lander mission is to search for evidence of biosignatures on Europa.**

Critically, the Europa Lander mission would advance our scientific understanding of fundamental aqueous and geochemical processes in the solar system, independent of whether or not signs of life are discovered on Europa. **The second science goal of the mission is to assess the habitability of Europa via in situ techniques.** As part of this goal, measurements would be conducted that could help remove ambiguities associated with detecting signs of life. The same measurements would also help determine the composition of the sampled surface material, and the proximity of the lander to any subsurface liquid water. These measurements would serve to constrain the composition of Europa's ocean and its relationship to the ice shell and rocky seafloor.

The third and final goal of the mission is to characterize the surface and subsurface to enable future robotic exploration. Through this goal the measurements of the first two goals would be framed in the broader context of Europa as a potentially active and dynamic ocean world, and the measurements associated with this goal would ensure that future robotic missions could explore across Europa's landscape, or deeper within the ice shell and ocean. The measurements made as part of the three Europa Lander science goals would also **extend and enhance the remote sensing observations of the Europa Clipper Mission** by performing in situ analytical investigations of Europa's surface materials and ice shell, thereby providing valuable ground-truth measurements.

Motivation

The science Goals of the Europa Lander mission concept address three of NASA's "Big Questions" (NASA, 2017) that currently motivate planetary exploration:

1. How did life begin and evolve on Earth, and has it evolved elsewhere in the Solar System?
2. What are the characteristics of the Solar System that lead to the origins of life?
3. Are we alone?

In addition, the mission concept goals and objectives are directly traceable to multiple science priorities described in the 2011 Decadal Survey *Vision and Voyages for Planetary Science in the Next Decade 2013–2022* (NRC, 2011). Detailed science objectives flow directly from the high-level mission goals, as shown in the abbreviated science traceability matrix in the Europa Lander SDT report (Europa Lander Study, 2016).

For each science objective, a generic notional instrument is indicated in the SDT report that would be capable of acquiring the types of measurements required. The mission concept could be successfully conducted using a range of science payload configurations, in which different instrument types from these generic classes are integrated. However, in order to demonstrate the overall scientific and technical viability of the Europa Lander mission concept, two example payload configurations (Baseline and Threshold) were developed in detail, based on flight-proven technologies that could be adapted to Europa conditions. These example model payloads fit within the currently-established engineering constraints of the Europa Lander mission concept, and achieve the Baseline and Threshold level science requirements.

Mission architecture

The high-level Europa Lander mission concept architecture was defined, for the purpose of the Science Definition Team (SDT) activity, by NASA HQ and the JPL Europa Lander pre-project team. These design requirements include the following: the lander would be launched by a Space Launch System (SLS) rocket separately from Europa Clipper and would include a Carrier Relay Orbiter (CRO) spacecraft to support data relay to and from the Europa Lander; Europa Clipper would only serve as a back-up telecommunications link. The Europa Lander, therefore, would be a stand-alone surface mission, operating independently of the precursor Europa Clipper mission, but guided by landing site reconnaissance enabled by Europa Clipper.

Several power systems were considered for the Europa Lander, with the final determination that primary batteries would provide for sufficient lifetime on the surface to achieve the Baseline science requirements. Primary batteries provide 45 kWh of energy, supporting operations in the mission design presented here and in the SDT report. Several surface operations scenarios were considered, yielding a range of surface lifetimes from approximately 20 to 40 days on Europa's surface. Importantly, due to Europa's harsh radiation environment, the lifetime of the supporting CRO would be limited to ~30 days in orbit around Europa, thus making a longer-lived lander mission difficult to justify. **The lifetime of the lander is 20+ days on Europa's surface, for a Baseline surface phase operations scenario in which five samples (each acquired from 10 cm below the surface), are processed, analyzed, and the data uplinked/downlinked through the CRO to Earth.** The Baseline scenario provides for schedule margin on sample acquisition, and for science team ground-in-the-loop operations to determine which samples to acquire.

The Europa Lander mission concept provides 42.5 kg for the Baseline science instrument payload (32.3 kg without recommended margin). With the exception of the Context Remote Sensing Instrument (CRSI), all instruments are held within a vault that provides radiation shielding. The centerpiece instruments for characterizing any potential signs of life are:

1) an Organic Compositional Analyzer (OCA), which in the Baseline model payload is a Gas Chromatograph-Mass Spectrometer (GC-MS) **capable of achieving a 1 picomole per gram of sample limit of detection for organics**,
2) a microscope system (referred to as the Microscope for Life Detection, MLD) **capable of distinguishing microbial cells as small as 0.2 microns in diameter, and as dilute as 100 cells per cubic centimeter (cc, or equivalently 1 mL) of ice**. In the Baseline model payload this capability is to be addressed by a combinations of spectroscopy and atomic force microscopy (AFM) or optical light microscopy (OM), and,

3) a Vibrational Spectrometer (VS), which in the Baseline model payload is a Raman and Deep UV fluorescence spectrometer **capable of characterizing both organic and inorganic compounds down to a level of parts per thousand by mass**.

Along with the analytical suite for detailed analyses of samples, the Europa Lander model payload also includes a pair of color stereo imagers (CRSI) for examining the landing site in 3-D (including capabilities for characterizing surface composition), and a seismic package for determining Europa's ice shell and ocean thickness through acoustic monitoring of cracking events in the ice shell.

Science investigations

Science Goal #1 is to Search for Evidence of Biosignatures on Europa. No singular measurement would provide sufficient evidence for the detection of life on Europa; rather, the conclusion that evidence of **life had been detected would require multiple lines of evidence, from different instruments, on a set of samples examined across a variety of spatial scales.** Through the combination of the OCA, VS, MLD, and CRSI, the model payload for the Europa Lander presents at least nine different and complementary possible lines of evidence for signs of life in samples collected on Europa. These measurements range from detecting and characterizing organic compounds, to looking for cell-like structures, to determining if the samples originate from within Europa's ocean or other liquid water environments. The organic chemical analyses are specifically targeted to reveal the broadest possible range of signatures produced by life, including analysis of molecular type, abundance, and chirality. Spectroscopic analyses of samples provide the inorganic and geochemical context of the samples, and enable discrimination between material native to Europa (endogenous) and materials that may have been externally delivered (exogenous, e.g., from micrometeorites), or processed by Europa's radiation environment. Collection of five separate samples, each of at least 7 cc total volume, provides for repeated measurements, ensuring redundancy and robustness of results. Detection limits for measurements targeting evidence of life were established by comparison to several extreme, nutrient limited environments on Earth. Importantly, the model payload and measurements defined for Goal 1 generate highly valuable scientific results even in the absence of any signs of life.

Science Goal #2 is to Assess the habitability of Europa via in situ techniques uniquely available to a lander mission. If the measurements from Goal 1 reveal potential biosignatures, then it is important to understand the geochemical context for habitability, and the proximity of the landing site to habitable regions within Europa's ice shell and ocean. However, if the measurements of the samples and landing site reveal no definitive biosignatures, then it becomes essential that ambiguous or null results are understood in the broader context of Europa's habitability. Investigations of habitability include characterizing the non-ice composition of Europa's near-subsurface to discern indicators of chemical disequilibria and other key environmental features that are essential to support life. In addition, Goal 2 addresses the need to understand the relationship of the landing site and samples to any liquid water, i.e., a subsurface ocean or regions within the ice shell. Goal 2 investigations are achieved primarily through measurements made by the VS, GSS, and CRSI, with some contributions from the MLD and OCA. Significantly, the in-situ measurements made by the lander would link nested observations across multiple scales to the observations of the Europa Clipper mission. The local-scale observations (submicron to decameter) of the lander would provide ‘ground truth’ measurements that would permit refined interpretation of remote sensing data across the surface of Europa.

Science Goal #3 is to Characterize surface and subsurface properties at the scale of the lander to support future exploration. The Europa Lander mission concept described in the SDT report is a ‘pathfinder’ for the exploration of Europa, and potentially many other ocean worlds of the outer solar system. As a stationary, relatively short-lived mission, this spacecraft would survey the landscape and probe the subsurface (acoustically) to determine the physical and chemical conditions on, and within, Europa. These measurements would then feed forward into designs of future robotic vehicles that would explore across the surface, or down into the subsurface. The nature of the landing environment, mobility hazards, and (near) surface physical properties within the workspace accessible to the lander’s robotic arm, are all key characteristics to observe and directly quantify as part of Goal 3. Investigations include characterizing textural, structural and compositional heterogeneities in surface and near-surface materials through measurements of the samples (with the VS, MLD, and OCA), and through observations of the terrain, from the lander workspace to the horizon and into the ice shell (with the CRSI and GSS). In addition, tidal and other dynamic motions would be investigated over the surface mission duration by monitoring the lander’s position with respect to the CRO. Goal 3 also leverages engineering support data from the descent hazards imaging LIDAR and descent imaging systems (on the Powered Descent Vehicle that delivers the lander safely to the surface) and from the robotic arm and accelerometers on the lander. These datasets would help further constrain the ice shell properties, and span the image resolution gap from flyby images to surface images collected by the lander CRSI. The combination of these multi-scale measurements would aid in understanding the physical and mechanical properties of the ice shell and any associated regolith, and would directly support future robotic exploration.

The science addressed by the three Goals leads to a **fully integrated mission concept and model payload that would enable a diverse approach to the search for potential biosignatures, bring-ing together morphological, organic, chiral, and inorganic indicators of life, all within a well-quantified geological context**. Chemical analyses of samples collected directly from Europa’s near surface layer would provide for characterization of organics at the picomole-per-gram level of sampled material, which is an improvement of approximately **nine orders of magnitude over those possible by means of remote sensing capabilities**. Quantitative high-resolution imaging observations from lander instruments would span scales from fractions of micrometers to decameters (0.2 microns to tens of meters) to provide in situ context for sampled materials, local geology, and surface properties. This roughly **seven orders of magnitude enhancement in spatial resolution** over the Europa Clipper mission would provide key insights into the properties of Europa’s ice shell and any subsurface liquid water. Further, the acoustic sounding measurements would provide unique and complementary measurements to those performed by the radar, magnetometer, and plasma instruments which will be flown on Europa Clipper.

The scientific and technical approach of the Europa Lander mission concept presented in the study (Europa Lander Study, 2016) provides a robust, yet conservative, strategy for the first landed mission to search for signs of life on an ocean world.

The science return possible from the model payload is such that **if life is present in Europa's ice at a level comparable to one of the most extreme and desolate of environments on Earth (Lake Vostok ice) then this mission could detect life in Europa's icy surface.** The combination of detection methods, detection limits, and scales of observations provided by the model payload and mission concept combine to make this possible. In the absence of any signs of life, this mission is also designed to generate an incredibly valuable dataset about the chemistry of Europa's ice shell, its putative ocean, and the geological, geophysical, and chemical context for habitability. Either of the above outcomes is of fundamental scientific value to understanding the prospects for life in the solar system, and our place in it.

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The Astrobiology of the Anthropocene

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Introduction: This is the Anthropocene

Human influence on the biosphere has been evident at least since the development of widespread agriculture over 10,000 years ago, and some stratigraphers have suggested that the activities of modern civilization indicate a geological epoch transition. Materials such as plastics, concrete, and other "technofossils" will continue to join the products of fossil fuel combustion as a uniquely anthropogenic contribution to the sedimentary record, while geochemical residues from pesticides and fertilizers will also remain in the rock record (Waters et al. 2016). Fallout from nuclear tests likewise constitute a detectable signature, which has led to the suggestion of demarcating the Holocene-Anthropocene boundary at the time of the world's first nuclear bomb explosion in 1945 (Zalasiewicz et al. 2015).

Future changes in the Earth system could also leave stratigraphic signatures. Some modeling studies have suggested that anthropogenic climate change could delay or even halt the ice-age cycle (Herrero et al. 2014; Haqq-Misra 2014). Proposals to counteract climate change through intentional geoengineering include the idea of actively promoting the growth of thick ice sheets in order to alter Earth's energy balance (Haqq-Misra 2015; Desch et al. 2017) and injecting sulfate particles into the stratosphere to increase cloud albedo (Vaughn & Lenton 2011; Moreno-Cruz & Keith 2013), both of which could contribute to changes in stratigraphy. Social instability could also leave a stratigraphic signature, such as the catastrophic consequences following a global nuclear winter (Robock et al. 2007).

Our perspective as a civilization living within the epoch transition from the Holocene to the Anthropocene allows us to contemplate the emergence of technological civilization in the context of planetary-scale processes (Grinspoon 2016). The Anthropocene may even represent a predictable planetary transition in general, to the extent that any energy-intensive species should drive changes in its biosphere (Frank et al. 2017). Examining the Anthropocene epoch through the lens of astrobiology can help to understand the future evolution of life on our planet and the possible evolution of technological, energy-intensive life elsewhere in the universe.

Climate Change as a Planetary Process

Climate change is one of the most salient science and political issues of our time. From an astrobiological perspective, drastic climate changes such as the Great Oxygenation Event (or Oxygen Catastrophe) at the beginning of the Proterozoic, the Neoproterozoic Snowball Earth episodes, or the Paleocene-Eocene Thermal Maximum (McInerney & Wing 2011) have led to major shifts in the dominant forms of life on Earth. The Permian-Triassic extinction event, also known as the "Great Dying," may have been caused in part by the production of methane by the archaea *Methanosarcina* (Rothman et al. 2014). A methanogen-dominated biosphere may have also generated a protective haze layer during the Archean to maintain habitable conditions (Arney et al. 2017). Such events illustrate the ability of life to act as a transformative process on a planet, shaping the conditions that will accommodate future lifeforms. Yet Earth has remained continuously inhabited for almost 4 billion years while going through a wide range of immense environmental and atmospheric changes. Methods for inferring properties such as the air density (*e.g.*, Kavanagh & Goldblatt 2015; Som et al. 2016), temperature (*e.g.* Valley et al. 2002), and redox state (*e.g.* Catling & Claire 2005) of Earth's atmosphere through geologic time give snapshots of known inhabited worlds different from modern Earth. The study of Earth's habitability through geologic time provides a basis for understanding how the Earth system will respond to anthropogenic contributions in the future.

Comparative planetology provides another route for understanding climate processes in a broader physical context. Study of the atmospheres of Mars, Venus, and Titan, past and present, provide important observable examples of how planets undergo long-term climate evolution. Theoretical studies of planetary habitability climate tend to push the climate models into non-Earth regimes that are relevant for exoplanet characterization, such as synchronous rotation, extremely high carbon dioxide, and other exotic orbital configurations. The concept of a runaway greenhouse can explain the history of Venus (Way et al. 2016) and delineate the inner edge of the habitable zone (Kopparapu et al. 2013), which has also inspired investigation of the threshold at which anthropogenic activity could induce a runaway greenhouse on Earth today (Goldblatt et al. 2013; Ramirez et al. 2014; Popp et al. 2016). Accurate representation of clouds is important for exoplanet climate models, which has also been identified by the Intergovernmental Panel on Climate Change (IPCC) as a critical area of improvement needed for Earth models. The exoplanet climate modeling community has made significant progress over the past five years toward improving our understanding of large-scale cloud processes for synchronously rotating planets (Yang et al. 2013), runaway greenhouse thresholds (Leconte et al. 2013), and other habitability constraints (*e.g.*, Fujii et al. 2017; Kopparapu et al. 2017; Turbet et al. 2017).

Exoplanet atmospheric characterization is a related emerging area of interest that provides additional data for understanding how atmospheres evolve, which includes recent discoveries like Proxima Centauri b, the TRAPPIST-1 system, LHS1040b, and Ross 128b. Comparative modeling studies within the exoplanet science community could also benefit from interdisciplinary collaboration with the Earth climate community, especially to support mutual model development goals.

Future projections of climate change on Earth show a range of likely outcomes, which depends in part upon humanity's response to engage in mitigation, adaptation, and (perhaps) geoengineering. Geoengineering research is not within the scope of the astrobiology program, but interdisciplinary collaboration with geoengineering groups could also lead to progress on both present-day climate and exoplanet habitability problems. One possible link is understanding the role of geoengineering in the long-term future of Earth (Goldblatt & Watson 2012), which could help to predict potential remote signatures of geoengineering on exoplanets.

The Limits and Lifetime of Human Civilization

Beyond the present-day climate problem, any growing technological civilization living on a finite planet will face limits and consequences to growth, while enduring self-induced or extant threats that compound with time. This realization prompted Thomas Malthus' warnings in 1789 about the limits of human population growth and the effects on the environment and agricultural systems, which suggested that a civilizational collapse was possible. Subsequent analyses in the following centuries adjusted the threshold of this collapse based upon the ability of technology to raise a planet's carrying capacity.

A modern analysis of this problem with recent population and agricultural data finds that growth in the food supply should continue to outpace current trends in population in the foreseeable future (Mullan & Haqq-Misra 2018). However, this analysis also finds that, even if greenhouse gas emissions are mitigated, growth in human civilization's energy use will thermodynamically continue to raise Earth's equilibrium temperature. If current energy consumption trends continue, then ecologically catastrophic warming beyond the heat stress tolerance of animals (Sherwood & Huber 2010) may occur by ~2200-2400, independent of the predicted slowdown in population growth by 2100 (Raftery 2012).

The limits imposed by thermodynamics on a growing civilization suggest that such effects could be a universal feature of planets that have undergone an Anthropocene-like transition (Frank et al. 2017). The predicted fractional change in temperature ($\Delta T/T \sim 2\%$) at this thermodynamic limit corresponds to a world power use of $O(10^{16})$ W (compared to the $O(10^{13})$ W for today), or about 7% of the incoming solar radiation (Mullan & Haqq-Misra 2018). Further work is needed to determine whether this is a hard limit to energy consumption, or whether this limit depends on second order climate effects, ecosystem stability, atmospheric composition, orbital distance, planetary radius, or other properties of a civilization's host planet.

The existence of thermodynamic growth limits for human civilization also suggests possible explanations for the Fermi paradox and strategies in the search for extraterrestrial intelligence (SETI). Calculations of the mean lifetime of energy-intensive civilizations help place general planetary habitability models into the specific context of civilizational habitability, which implies that sustainability limits should apply in general to civilizations everywhere (Frank & Sullivan 2014). The $O(10^{16})$ W energy limit coincidentally corresponds to a "Type-I" civilization according to the Kardashev scale, which may point toward a fundamental limit of the observational imprint of a developing civilization.

Other risk factors could also reduce the longevity of a technological civilization, which are often collectively referred to as global catastrophic risks (Bostrom & Cirkovic 2008) or existential risks (Bostrom 2013). Such possibilities include nuclear winter, pandemic, and asteroid impacts, as well as projected catastrophic failures of future technologies, such as artificial intelligence. Collaborations with research communities that study global catastrophic and existential risks would help to develop quantitative constraints on the expected mean lifetime of energy-intensive civilizations. Such constraints would improve policy decisions for the future of human civilization and also guide SETI toward targets most likely to host extant civilizations.

Searching for Other Civilizations

Civilization and technology emerged once from the planetary processes on Earth, which provides an example of what to look for elsewhere. This does not necessarily imply that other inhabited planets will follow the same trajectory as life on Earth. Instead, SETI tends to operate with the working hypothesis that anything that happened here on Earth, or that is possible to happen in the future, remains a plausible option for guiding the search for other civilizations.

SETI has so far managed to continue its efforts by appealing to the private sector for funding, such as the Breakthrough Listen initiative (Enriquez et al. 2017) as well as nightly surveys by the SETI Institute using the Allen Telescope Array (Harp et al. 2016). SETI represents an important objective of astrobiology, as progress in identifying and characterizing exoplanets also allows SETI to select better targets. This is an area for continued collaboration, in order to allow the observational and theoretical habitability studies from within astrobiology to also benefit SETI research (Frank & Sullivan 2016).

Spectral signatures provide one way to characterize a planet's atmosphere, with a sizable astrobiology literature on possible atmospheric biosignatures that could indicate the presence of surface life (*e.g.*, Schwieterman et al. 2018). Spectral technosignatures are a particular spectral signature that would indicate the presence of a technological civilization on the planet (Schneider et al. 2010; Stevens et al. 2016). Examining the effects of human civilization on Earth's climate, both today and in likely future trajectories, can help to identify plausible technosignatures that might be observed with the next generation of space telescopes.

The terraforming of otherwise uninhabitable planets within a planetary system is one example of a possible technosignature, where powerful artificial greenhouse gases may be deployed to warm a planet outside the formal habitable zone (Fogg 2010). Such planets may be identified from the spectral features of greenhouse gases such as perfluorocarbons (PFCs), which are not known to otherwise occur in high abundances. Spectral technosignatures would produce the most observable features in the infrared portions of the electromagnetic spectrum, specifically in the thermal infrared window region at 8-12 μm for greenhouse gases. Conceptual studies of space telescopes capable of imaging terrestrial planets in the mid-infrared were previously studied, such as NASA's Terrestrial Planet Finder Infrared (TPF-I) space-based interferometer design concept (Beichman et al. 2006), and ESA's Darwin concept (Cockell et al. 2009), although neither is currently under consideration by either agency. The Origins Space Telescope (OST) concept is currently under study, which could resolve terrestrial planet features in the 8-12 μm range (Cooray et al. 2017).

The search for megastructures, such as Dyson swarms or other artifacts of extraterrestrial engineering, complements existing spectral surveys. The observation of anomalous absorption in the KIC 8462852 system (also known as "Boyajian's Star") prompted speculation on the possibility of detecting megastructures through transit photometry (Wright & Sigurdsson 2016; Gaidos 2017). Astrobiologists may therefore inevitably find themselves part of this discussion, particularly if future missions detect other unusual transit or spectral features.

Sustaining the Overview Effect

The "overview effect" is a feeling described by astronauts as a cognitive shift in awareness that comes from viewing the Earth from space. A common expression of the overview effect is a profound understanding of the interconnection of all life and a renewed sense of responsibility for taking care of our planet (White 2014). Even for those not fortunate enough to experience the view firsthand, the overview effect can still be expressed and felt by standing on Earth's surface. This was perhaps most poignant with the release of the iconic Earth-from-space images from Apollo 8 and Apollo 11 that continue to endure in popularity today (Chaikin 2007).

Images convey emotions that words cannot, and modern space missions all have cameras for this reason. Carl Sagan's "Pale Blue Dot" image of Earth taken from Voyager 1 inspired other initiatives, such as the "Pale Blue Orb" image of Earth taken from Cassini. Similar impressions of awe and wonder occur when viewing the Hubble Deep Field images. Improvements in data bandwidth technologies have also led to new Earth-observing platforms. For example, the Japanese Himawari 8 and American DISCOVR weather satellites are uniquely positioned to observe the whole terrestrial disk and operate websites for the public to view real-time Earth images. The International Space Station also broadcasts a live image stream of Earth from space.

The Large Ultraviolet Optical and InfraRed (LUVOIR), Habitable Exoplanet Imaging Mission (HabEx), and OST are three space telescope concepts currently under study by NASA that would provide unprecedented advances in the study of exoplanets and extragalactic astronomy (Dalcanton et al. 2015; Bolcar et al. 2017; Mennesson et al. 2016; Crill & Siegler 2017), both of which are areas with notable public interest. If any of these next generation observatories is deployed, then consideration should be given to observations of images that resonate with the public, much as the Hubble Deep Field images provided broad appeal beyond immediate science goals.

Conclusion and Recommendations

The study of the anthropocene as a geological epoch, and its implication for the future of civilizations, is an emerging transdisciplinary field in which astrobiology can play a leading role. We recommend two approaches toward making significant progress in this area:

- The NASA Astrobiology Institute should establish a Focus Group on the "astrobiology of the Anthropocene." This focus group would develop a subcommunity of scholars interested in studying Earth's future, drawing from within the astrobiology community as well as drawing upon other experts from the climate change, geoengineering, SETI, security, education, and risk communities.

- NASA should maintain the development of missions such as LUVIOR, HabEx, and OST, which will provide the best opportunity in the coming decades to observe terrestrial biosignatures. Future decadal surveys should consider mission concepts similar to TPF-I and Darwin, or even a lunar observatory, in order to characterize biosignatures and possible technosignatures in the thermal infrared region.

Roadmaps to Ocean Worlds (ROW): Goals, Objectives, Investigations

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1. The Roadmaps to Ocean Worlds (ROW) Statement of Task

The 2016 Congressional Commerce, Justice, Science, and Related Agencies Appropriations Bill (hereafter CJS) directed NASA to create an Ocean Worlds Exploration program, using a mix of programs already established within NASA. Their direction for this program was to seek out and discover extant life in habitable worlds in the Solar System. In support of these efforts, the Outer Planets Assessment Group (OPAG), with cooperation from NASA's Planetary Science Division, formed the Roadmaps to Ocean Worlds (ROW) group to assemble the scientific framework guiding the exploration of Ocean Worlds, which can serve as input to the Planetary Decadal Survey mid-term review and the next full Survey. ROW was given the following charter:

- Identify and prioritize science objectives for ocean worlds over the next several decades
- Design roadmap(s) to explore these worlds to address science objectives (including mission sequences, considering a sustained exploration effort)
- Assess where each ocean world fits into the overall roadmap
- Summarize broad mission concepts (considering mission dependencies and international cooperation)
- Recommend technology development and detailed mission studies in support of the next Decadal Survey

The team is co-chaired by Terry Hurford and Amanda Hendrix, who organized a large team of individuals with expertise in the various related disciplines, including small bodies topics normally covered by the Small Bodies Assessment Group (SBAG), to provide inputs for this and future reports. The ROW team membership is detailed on the cover page of this white paper.

This white paper describes the scientific content and priorities for investigations that are needed for the exploration of ocean worlds. Such investigations would be carried out by a robotic flight program that would measure needed quantities at ocean worlds, and by research efforts to characterize important physical processes potentially at work on ocean worlds.

2. Definition of Ocean World

For the purposes of this document, and to bound the extent of a future Ocean Worlds program, we define an "ocean world" as a body with a current liquid ocean (not necessarily global). All bodies in our solar system that plausibly can have or are known to have an ocean will be considered as part of this document. The Earth is a well-studied ocean world that we use as a reference ("ground truth") and point of comparison. We do not include the ice giant planets as ocean worlds.

3. Philosophy, Goals, Objectives, and Major Findings

There are several – if not many – ocean worlds or potential ocean worlds in our Solar System, all targets for future NASA missions in the quest for understanding the distribution of life in the Solar System. This white paper lays out the science questions and investigations to be addressed for each of those targets, and in doing so is designed to be the first part of a roadmap for charting the course to search for life at ocean worlds in our Solar System.

In considering ocean worlds, there are several with confirmed oceans, several candidates that exhibit hints of possible oceans, and worlds in our Solar System that may theoretically harbor oceans but about which not enough is currently known to determine whether an ocean exists. As a philosophy, the ROW team deems it critical to consider all of these worlds in order to understand the origin and development of oceans and life in different worlds: does life originate and take hold in some ocean worlds and not others, and why? Thus, **the ROW team supports the creation of a program that studies the full spectrum of ocean worlds**; if only one or two ocean worlds are explored and life is discovered (or not), we won't fully understand the distribution of life, its origin and variability, and the repeatability of its occurrences in the Solar System.

The House CJS Appropriations 2016 bill explicitly identifies Europa, Enceladus, and Titan as ocean worlds. We have considered that Enceladus, Europa, Titan, Ganymede and Callisto have known subsurface oceans, as determined from geophysical measurements by the *Galileo* and *Cassini* spacecraft. These are *confirmed* ocean worlds. Europa and Enceladus stand out as ocean worlds with evidence for communication between the ocean and the surface, as well as the potential for interactions between the oceans and a rocky seafloor, important for habitability considerations. The subsurface oceans of Titan, Ganymede and Callisto are expected to be covered by relatively thick ice shells, making exchange processes with the surface more difficult, and with no obvious surface evidence of the oceans.

Although Titan possesses a large subsurface ocean, it also has an abundant supply of a wide range of organic species and surface liquids, which are readily accessible and could harbor more exotic forms of life. Furthermore, Titan may have transient surface liquid water such as impact melt pools and fresh cryovolcanic flows in contact with both solid and liquid surface organics. These environments present unique and important locations for investigating prebiotic chemistry, and potentially, the first steps towards life.

Bodies such as Triton, Pluto, Ceres and Dione are considered to be *candidate* ocean worlds based on hints from limited spacecraft observations. For other bodies, such as some Uranian moons, our knowledge is limited and the presence of an ocean is uncertain but they are deemed *credible possibilities*.

The ROW team decided on an overarching goal for the roadmaps: **Identify ocean worlds, characterize their oceans, evaluate their habitability, search for life, and ultimately understand any life we find**. This overarching goal naturally can be subdivided into four underlying goals, each of which has 2-3 objectives:

Goal I: Determine which bodies have oceans and understand how to determine whether other bodies host current oceans.

A. Is there a sufficient energy source to support a persistent ocean?

B. Are signatures of ongoing geologic activity (or current liquids) detected?

C. How do materials behave under conditions relevant to any particular target body?

Goal II: Characterize the oceans.

A. Characterize the physical properties of the ocean and outer ice shell

B. Characterize the ocean interfaces

Goal III: Characterize the habitability of the oceans.

A. What is the availability (type and magnitude/flux) of energy sources suitable for life, how does it vary throughout the ocean and time, and what processes control that distribution?

B. What is the availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?

Goal IV: Understand what kind of life could be present in these oceans and how to search for it, and understand the biology.

A. What are the potential biomarkers in each habitable niche? (determine what we're looking for)

B How to search for and analyze data in different environments?

The detailed Investigations associated with these Goals and Objectives are listed in the Goals document at https://www.lpi.usra.edu/opag/ROW/ and are also linked to Decadal Survey goals in that document. Figure 1 demonstrates the state of knowledge of each objective, for those prominent Solar System targets.

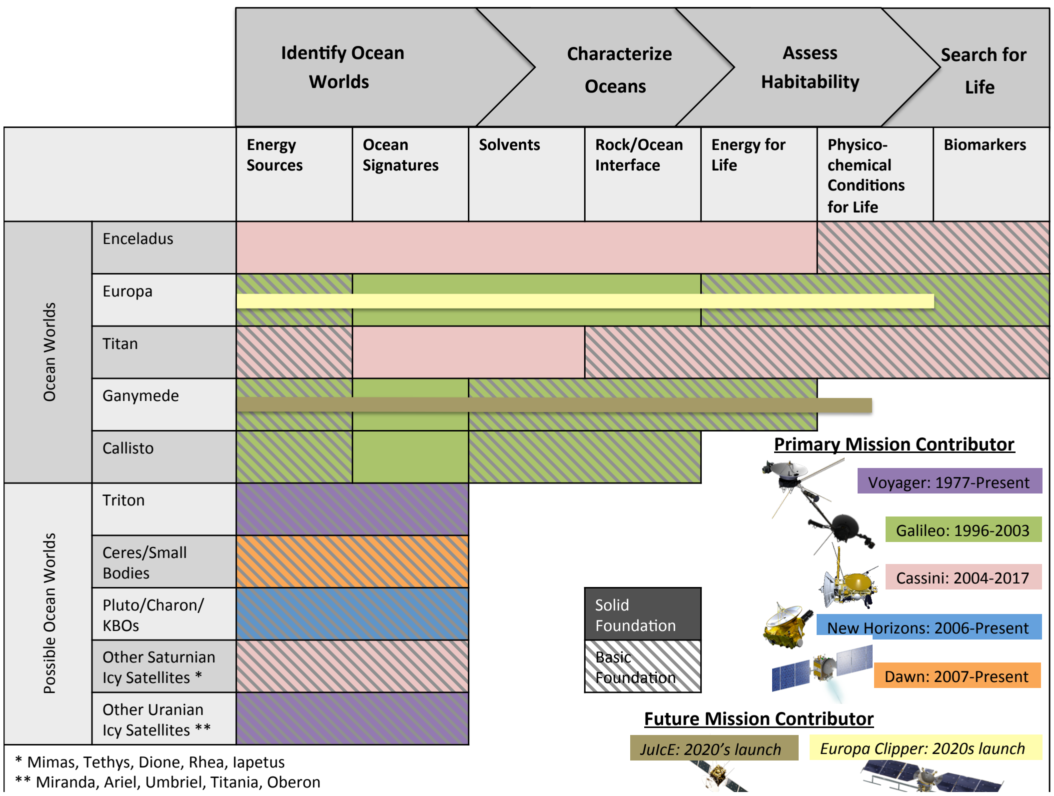

Figure 1. Investigations Roadmap: demonstrating the state of knowledge for each (potential) target world. Colors represent the missions that provided the majority of information about each target. An evaluation on how well each target is understood for the various science objectives has been included: a solid color represents a solid foundation for addressing the science objective while a hashed color represents only a basic foundation.

A major finding of this study is that in order to map out a coherent Ocean Worlds Program, significant input is required from studies here on Earth: rigorous Research and Analysis (R&A) studies are called for, to enable some future Ocean Worlds missions to be thoughtfully planned and undertaken. Many research objectives and investigations involve questions that can be addressed here on Earth – through modeling, field studies, lab work etc. so that spacecraft data can be best planned, acquired and interpreted. Most of the Ocean World mission candidate bodies are in the outer solar system, meaning that total mission duration can be decades in length, and to fully address the open science questions will likely require multiple missions to each body. Given these long timescales, such Earth-based investigations should be undertaken beginning immediately and continue on in parallel with planning and execution of Ocean Worlds missions. The objectives laid out in this document cover both those that include measurements required to be made at the various target bodies and measurements/studies that will need to be made here on Earth to prepare for those robotic measurements and to help in their interpretation. *Thus the ROW team recommends a rigorous R&A initiative as part of the Ocean Worlds Program; many of these R&A studies could be addressed as part of the current NASA R&A programs and it is recommended that Ocean Worlds be highlighted in those programs so that this work can be accomplished*.

A second finding is that progress needs to be made in the area of collaborations between Earth ocean scientists and extraterrestrial ocean scientists. We can harness the >100 years of ocean research that has been done on Earth and bring that to bear on future studies that help move the Ocean Worlds program forward. To stimulate a program of comparative oceanography will require coordination between agencies. Classical oceanography might not currently fit well within NASA's R&A portfolio; however the work that NSF (process studies), NOAA (exploration) and ONR (technology, specially autonomy/robotics) all do in supporting different aspects of ocean research on Earth, is something that they tend to only support under conditions (P, T, ocean salinity, seafloor composition) that pertain specifically to Earth. To extend this basis of Earth-centered knowledge into the solar system will be a challenge and requires a shared vision among the above agencies. *Thus the ROW team recommends the establishment of a working group to study the specific research areas that can be investigated by direct collaborations between the Earth ocean and the Ocean World communities.*

4. Links to the 2013-2022 Planetary Science Decadal Survey and Solar System Exploration

The types of investigations and target bodies of interest to an Ocean Worlds Program are included primarily within the Satellites Theme (Chapter 8) of the 2013-2022 Planetary Science Decadal Survey (Squyres et al. 2011). Within that Theme, the goal of determining "What are the processes that result in habitable environments?" most explicitly connects to the Ocean World Objectives. Additionally, Ocean Worlds are clearly a large part of the Habitable Planets cross-cutting science theme, which includes the goal of determining "Beyond Earth, are there contemporary habitats elsewhere in the Solar System with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?"

Many of the Ocean Worlds Objectives also tie into geologic history-focused questions – such as the Satellite goals of "How did the satellites of the outer Solar System form and evolve?" and "What processes control the present-day behavior of these bodies?" and the Primitive Bodies goal of "Understanding the role of primitive bodies as building blocks for planets and life." These connections are often indirectly related (i.e., they require similar measurements even though the driving question differs) – as the focus of the Decadal Survey is on understanding each type of target body, versus the higher-level Ocean Worlds aim to understand how we can best identify and characterize habitable oceans, and ultimately perhaps life, within these bodies.

5. Links to broader outer Solar System research objectives

ROW-related investigations have close links with science goals pertaining to mission targets throughout the outer Solar System. Identifying ocean worlds and assessing their habitability will be enabled by detailed investigations of many targets even if they do not directly possess oceans themselves. For example, Io is a laboratory for understanding tidal heating, a process that is critical to sustaining ocean worlds. Although Io is not an "ocean world" in the sense used here (despite its potential internal magma ocean), careful application of the lessons learned from studying Io's thermal inventory will prove invaluable in the pursuit of science objectives described throughout this document. Similarly, Ceres is thought to have hosted a global ocean in its early history; this ocean would have frozen within the first few hundred million years of Ceres' evolution, unless convective mixing in a muddy interior slowed down heat loss. A briny layer mixed with silicates could remain at present at the interface between Ceres' crust and mantle, consistent with thermal modeling. Likewise, a more complete understanding of the interiors of the ice giants (e.g., from a dedicated mission) is critical to understanding the evolution of potential ocean worlds around these planets (e.g. Triton, Ariel, Miranda). Specifically, the tidal dissipation factor (Q) of a planet is critical to driving the dynamics and heating in these systems. This factor is a complex function of the interior structure of the planet. The more we understand about ice giant interiors, the more we can learn about potential heat sources, to sustain oceans within the moons.

ROW investigations are also well-correlated to the overarching research goals of NASA's Planetary Science Division (PSD). Questions addressed under Goals I and II directly correspond to the goals of NASA's Solar System Workings program as they require consideration and investigation of the interior structures, orbital evolution, and the resulting potential surface modification of particular ocean worlds. Additionally, Goals III and IV correspond directly to the goals of NASA's Habitable Worlds program, which include assessing the astrobiological potential of ocean worlds, and to the Exobiology program, which places an emphasis on biosignatures and life elsewhere. Further, since ROW's target bodies may potentially serve as analogs for water-rich, habitable exoplanets and exomoons, all ROW investigations will also map directly to the research goals of NASA's Astrophysics Division, particularly in relation to the identification and characterization of "habitable exoplanets and/or their moons." ROW investigations are also applicable to "understanding the chemical and physical processes of exoplanets, including the state and evolution of their surfaces, interiors, and atmospheres," which is a primary goal of the Exoplanets Research Program.

Roadmaps to Ocean Worlds (ROW): Priorities

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The 2016 Congressional Commerce, Justice, Science, and Related Agencies Appropriations Bill (hereafter CJS) directed NASA to create an Ocean Worlds Exploration program, using a mix of programs already established within NASA. Their direction for this program was to seek out and discover extant life in habitable worlds in the Solar System. In support of these efforts, the Outer Planets Assessment Group (OPAG), with cooperation from NASA's Planetary Science Division, formed the Roadmaps to Ocean Worlds (ROW) group to assemble the scientific framework guiding the exploration of Ocean Worlds, which can serve as input to the OPAG goals document, Planetary Decadal Survey mid-term review, and the next full Survey. ROW is co-chaired by Terry Hurford and Amanda Hendrix; the ROW team membership is detailed on the cover page of this white paper. This white paper describes the scientific priorities in ocean worlds targets, based on the goals and objectives described in the ROW Goals, Objectives and Investigations document (posted at https://www.lpi.usra.edu/opag/ROW/ and summarized in a separate white paper).

Summary of Recommendations.
ROW advocates an Ocean Worlds (OW) program that utilizes different classes of missions (Flagships, New Frontiers, Discovery, and, as possible, smallsats to ride along with these missions) to address OW questions. These questions focus on 1) understanding where/why oceans are present, which allows for 2) characterizing ocean environments in these known ocean worlds. With known ocean environments it becomes important to 3) characterize their habitability and ultimately 4) search for extant life.

The extent of the Ocean World Roadmap. Search-for-life missions should take place at target bodies most likely to support life and should include science payloads that can yield important information (such as a broader context of the sample environment, characterization of prebiotic chemistry as a indication of how far toward life the conditions have progressed, or assessment of the habitability of the environment) even if life signatures are ambiguous or absent in that particular mission. If hints of biosignatures are found, an appropriate follow-on mission should be planned.

In light of the open-ended nature of this exercise, the ROW team finds it most appropriate to derive a roadmap of <u>initial</u> suites of missions that advance all OW objectives as outlined in the Ocean Worlds Goals, Objectives and Investigations document, with follow-on plans to any one body entirely dependent on what is found during the initial missions. In other words, in this Roadmap we do not plan for contingencies but rather focus on the important *next* missions to send to different bodies in the ocean worlds spectrum, along with the needed technologies for development. It is assumed that if a <u>possible</u> ocean world moves to the category of <u>known</u> ocean world, this Roadmap would be updated and steps would then be taken to characterize that ocean, its habitability, etc. In addition, since the primary goal of ROW is to influence the 2023-2032 Decadal Survey, we focus here on priorities that can potentially be addressed in the next decade.

Priorities: Summary
The ROW team finds that the <u>known</u> ocean worlds Enceladus, Titan and Europa are the highest priority bodies to target in the near term to address OW goals. Triton is the highest priority <u>possible</u> ocean world to target in the near term.

1. Known Ocean Worlds

Europa, Titan and Enceladus are known ocean worlds and each is a compelling target in different ways. As known ocean worlds, the next step on the OW goals list for these bodies is to characterize habitability (as needed) and then, when/if habitability is deemed adequate for life, to search for life.

Ganymede and Callisto are also known ocean worlds, of lower priority in the Roadmap in terms of characterizing habitability or searching for life. Because these oceans are deeper and there is no evidence of communication between liquid water and the surface and/or a silicate core, oceans at Ganymede and Callisto should be better understood before exploring them as potentially habitable. This lack of knowledge limits their ability to support more of the Ocean World science objectives and thus they are lower in priority from other known ocean worlds.

1.1 Target Summary and Recommendations

Enceladus: The habitability of **Enceladus**' ocean has been sufficiently established using Cassini measurements, and thus to address OW goals, a search-for-life mission could be sent as a next step.

Enceladus Recommendations for Decadal Survey and Survey Preparation: The ROW team strongly recommends that a search-for-life mission at Enceladus be of high priority. Enceladus mission architectures that address the search for life should be studied in advance of the next Decadal Survey. New technologies may need development in addition to that funded for the New Frontiers 4 ELSAH concept.

Europa: Europa Clipper is a flagship mission in Phase B of development; the overarching goal of Clipper is to establish the habitability of Europa. An astrobiology-focused Europa Lander mission has been studied (Hand et al., 2017).

Europa Recommendations for Decadal Survey and Survey Preparation: The ROW team recommends that the Europa Clipper mission continue as planned for its importance in characterizing the habitability of Europa. The ROW team supports a Europa landed search-for-life mission, especially if the science payload can yield important astrobiological information even if biosignature results are ambiguous. Such a mission will advance the technologies needed to detect biosignatures at OW targets, especially from *in situ* measurements.

Titan: The habitability of **Titan**'s subsurface ocean and any interfaces between the ocean and surface, along with the surface lakes and seas of methane/ethane, has yet to be established. Thus, a habitability/ocean characterization mission to Titan is a natural next step to advance OW goals at this body. Numerous types of missions at Titan are possible. The Dragonfly mission concept has been selected for a Phase A study for NF-4.

Titan Recommendations for Decadal Survey and Survey Preparation: ROW considers missions to characterize Titan's ocean and assess its habitability to be of high priority. Even if Dragonfly is selected for NF4, additional Titan missions that advance the understanding of Titan as an OW should be studied prior to the Decadal Survey and considered by the DS panel.

Ganymede: The ESA JUICE mission is set to explore Ganymede. This mission will characterize Ganymede's subsurface ocean, located between layers of near-surface and high-pressure ices, to better understand the formation and evolution of this OW. It could place bounds on communication between the subsurface ocean and the surface, energy input into the ocean layer, and the habitability of oceans separated from underlying rocky mantles.

Ganymede Recommendations for Decadal Survey and Survey Preparation: The ROW team supports the ESA JUICE mission.

Callisto: This known OW remains to be fully characterized. Its deep subsurface ocean and its location on the edge of the Galilean satellite system limits not only communication between the ocean and the surface, but also vital energy input to the ocean. It may serve as an end member on the OW spectrum and help, along with Ceres, to characterize the limit of the ability of bodies to maintain oceans with sparse tidal input. In addition, because Callisto's ocean is also located between two layers of ices, Callisto studies could inform studies of Ganymede's ocean.

Callisto Recommendations for Decadal Survey and Survey Preparation: The ROW team supports mission studies to characterize Callisto's ocean and its sustainability. A smallsat mission to Callisto should be studied, that can perhaps advance OW objectives.

2. Possible Ocean Worlds.

Triton, Pluto, Ariel, Miranda and Ceres are among the possible ocean worlds in the solar system. Spacecraft data returned from these bodies suggest the possible presence of extant liquids in their interiors, but the size of any liquid reservoir is unknown. These bodies must be explored further to determine whether they have extant oceans and should be furthered studied as Ocean Worlds. The next missions to these bodies should establish the presence of oceans, perhaps using orbiting spacecraft (or multiple flyby missions) with magnetic, gravity field, libration, and/or topographic measurements of tidal flexing. Should extant oceans be found, future missions should characterize those oceans to establish their habitability and then potentially search for life.

In ranking the priority of the above worlds, we consider two factors: the timing of geological activity suggesting the presence of an ocean, and the likelihood of this activity being endogenic (including tidal) as opposed to exogenic (driven by insolation or impacts).

Other possible ocean worlds exist. However, the bodies listed here represent the most likely targets on which we can confirm oceans in the near future.

2.1 Target Summary and Recommendations

Triton: Of the above worlds, Triton is deemed the highest priority target to address as part of an Ocean Worlds program. This priority is given based on the extraordinary hints of activity shown by the Voyager spacecraft (e.g. plume activity; smooth, walled plains units; the cantaloupe terrain suggestive of convection) and the potential for ocean-driven activity given Cassini results at Enceladus. While the source of energy for Triton's activity remains unclear, all active bodies in the Solar System are driven by endogenic heat sources, and Triton's activity coupled with the young surface age makes investigation of an endogenic source important. Unlike other possible ocean worlds (such as Ceres or Pluto) observations of geologically recent activity make investigating and understanding its source of activity a priority. Furthermore, many Triton mission architectures would simultaneously address Ice Giant goals on which high priority was placed in the Visions & Voyages Decadal Survey. Finally, as Triton likely represents a captured Kuiper Belt object (KBO), some types of comparative planetology with KBOs could also be addressed in a Triton mission.

Triton recommendations for Decadal Survey and Survey Preparation**:** Prior to the next Decadal Survey, a mission study should be performed that would address Triton as a potential Ocean World; such as study could be part of a larger Neptune orbiter mission. The Decadal Survey should place high priority on Triton as a target in the Ocean Worlds program.

Pluto: Pluto is the first large object visited in the Kuiper belt and it shows young, potentially cryovolcanic terrains indicating activity may have continued through much of its history. As for Triton, the source of relatively *recent* internal heat on Pluto is not well understood, but models suggest an ocean may persist into the present. Studying large KBOs opens up a new regime for exploring ocean worlds in the solar system, and by comparative planetology helps us understand what is possible for icy moons that are not currently tidally heated.

Pluto recommendations for Decadal Survey and Survey Preparation**:** Mission studies should be performed to address technology advances enhancing exploration of the Kuiper belt or a return to Pluto with an orbiter (necessary to study a potential ocean). Studies to explore a potential KBO rendezvous as an extended part of another mission to the outer solar system (e.g., to a gas giant) are also encouraged.

Ariel and Miranda: After the Voyager flyby of the outer solar system, similarities between Enceladus, Miranda, and Ariel were noted. Only after Cassini's arrival were Enceladus' extant geological activity and ocean discovered. Miranda and Ariel both show evidence for recent significant tectonism that could indicate subsurface oceans.

Ariel and Miranda Recommendations for Decadal Survey and Survey Preparation: A mission to the Uranian system as outlined in the Ice Giant SDT study should set, as a top priority, flybys of these moons to search for evidence of subsurface oceans.

Ceres: Ceres is a unique case, a hydrous dwarf planet in the asteroid belt. Ceres is ~50% H_2O in volume and has a 40 km thick shell dominated by volatiles, with a density of 1.28 g/cm^3, but whether there is liquid water in its interior today is the subject of ongoing analyses of data from the Dawn spacecraft. Ceres is a small and heat-limited body, likely in the process of freezing, so it may provide an end-member scenario for medium-sized ocean worlds without tidal heating. Modeling and experimental research (utilizing R&A funding) in light of Dawn results would inform the understanding of ocean worlds as a whole.

Ceres Recommendations for Decadal Survey and Survey Preparation: A Ceres mission with a primary objective to detect and characterize any liquids within Ceres should be studied to determine how well small mission classes can help advance OW objectives.

3. Roadmap (Summary)

Based on the summary of targets above and the ROW recommendations, a broad outline of high priority missions can be developed as summarized here:

Highest priority targets:
Europa: Habitability mission– *Clipper in progress; Lander pre-AO study in progress*
Titan: Habitability/Ocean mission– *possibility of NF4 Dragonfly mission*
Enceladus: Search-for-life mission
Triton: Confirm/Characterize Ocean mission – *Triton orbiter or Neptune orbiter with Triton flybys (with magnetometer, gravity, thermal imagery, high-resolution imagery)*

The exact timing sequence of missions to execute depends on many considerations beyond the scope of ROW.

Canadian Science Priorities for Astrobiology

Abstract

This white paper reports on Canadian community interests with respect to astrobiology science objectives and potential participation in international missions related to astrobiology, as developed through a 2015-2017 community consultation exercise co-ordinated by the Canadian Space Agency. The resulting Canadian community Topical Team recommendations are pre-decisional, and no new Canadian investments can be assumed at this time.

Introduction

On 24-25th November 2016, 208 scientists, engineers and students associated with Canadian universities, industry and government gathered in Montreal to consider Canada's future in space under the Space Exploration theme '*Science and Space Health Priorities for the Next Decade and Beyond*'.

This consultation event was co-ordinated by the Canadian Space Agency (CSA) in the context of the Government of Canada's Innovation Agenda, and focussed on space exploration as an engine for innovation and a source for youth Science, Technology, Engineering and Mathematics (STEM) inspiration.

These discussions and ideas were further developed by the following eight Topical Teams (TT):

Astrobiology;
Planetary Atmospheres;
Planetary Geology, Geophysics and Prospecting;
Planetary Space Environment;
High Energy Astrophysics;
Cosmology;
Cosmic Origins; and,
Space Health.

Each TT was university-led, including industry and student representation, with a mandate to produce a specific chapter of the resulting community report: '*Canadian Space Exploration: Science and Space Health Priorities for Next Decade and Beyond*'. As a result, the chapters reflect the views of the communities as understood by the TT authors.

The chapters from these Planetary Science and Space Astronomy Topical Teams are currently available at ftp://ftp.asc-csa.gc.ca/users/ExP/pub/Publications/CSEW2016/TopicalTeams-EquipesThematiques/.

Canadian Science Priorities

Astrobiology was discussed in several Topical Teams, in addition to the Astrobiology Topical Team, reflecting its cross-cutting nature. A summary of priority science objectives is presented in Table 1, from which potential instrument and mission investigations are also identified in the chapters. For details, please refer to the chapters as linked above.

Table 1: Science Objectives most strongly related to Astrobiology from the 2017 Canadian Science Priorities report

Astrobiology Topical Team 21 members from 11 organisations
• AB-01 Biosignature Characterisation - understanding the target signs of life • AB-02 Biosignature Detection - developing the instruments that can detect signs of life • AB-03 Accessing the Subsurface for Astrobiology - below the harsh surface radiation environment of Mars, Europa and other astrobiology targets • AB-04 Accessing Special Regions - areas of Mars where temperature and availability of liquid water are believed most favourable for life • AB-05 Exoplanets: Characterisation and Detection of Biosignatures - remote sensing that can be applied to the search for life beyond our solar system.
Planetary Atmospheres Topical Team 19 members from 11 organisations
• PAT-01 Understand Mars Surface-Atmosphere Interactions -the present-day cycle of water on Mars • PAT-02 Understand the Chemistry of Planetary Atmospheres - the composition of atmospheres and trace gases that can indicate life or geological activity
Planetary Geology, Geophysics & Prospecting Topical Team 33 members from 17 organisations
• PGGP-03: Understand the origin and distribution of volatiles on the terrestrial planets and their moons asteroids and comets
Space Astronomy Cosmic Origins Topical Team 32 members from 14 organisations
• COR-05 - Direct imaging of nearby Earth-like exoplanets for biosignatures

The Canadian community Topical Team recommendations are pre-decisional, and no new Canadian investments can be assumed at this time.

Agnostic Biosignatures: Towards a More Inclusive Life Detection Strategy

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Abstract
A key scientific question in astrobiology is how to search for signs of life regardless of underlying biochemistry. Current strategies for biosignature detection rely on identification of well-established and widely accepted features associated with terrestrial life and signatures of biologic processes, such as particular classes of molecules and isotopic signatures, enantiomeric excesses, and patterns within the molecular weights of fatty acids or other lipids. As we begin to explore icy moons of Jupiter and Saturn and other destinations beyond Earth, a promising astrobiology research goal is the development of life detection methods that identify unknowable, unfamiliar features and chemistries that may represent processes of ***life as-yet unrecognized***. This objective requires us to utilize existing instrumentation in more inclusive ways, pursue new leads, and synthesize data with probabilistic approaches, as agnostic methods may trade definitiveness for inclusivity.

Introduction

"Life as we don't know it" presents a formidable challenge to any astrobiology strategy. How do we contend with the truly alien? What might the molecular and polymeric building blocks of life might look like on planetary bodies that are different from our own? Noteworthy advances have been made in this realm since the publication of the NASA's last astrobiology strategy, and significant progress is likely in the next twenty years. Building on foundational work that has been percolating in the astrobiology community[1], this document serves to illustrate some novel ways to detect chemical life without invoking any particular molecular frameworks.

> One promising research area for astrobiology is the detection of "agnostic" biosignatures—in other words, evidence of biology that doesn't presuppose a particular biochemistry.

Utilizing Existing Instrumentation in More Inclusive Ways

To cast the widest possible net for life detection, we must broaden not only the range of measurements we make but also the range of interpretations we allow. Part of this can be achieved by utilizing high heritage instrumentation or recently proven techniques with the potential to be developed into space qualified instrumentation in more agnostic ways. For example, flight capable mass spectrometers have long been flown on spacecraft, designed to search primarily for patterns among the molecular weights of carbon-bearing organic molecules. However, mass spectrometers can also be used, for example with tandem mass spectrometry[2], to search for chemical complexity of any type of molecule (organic or inorganic) that would be unlikely or impossible to form spontaneously.

The term "complexity" is often subjectively used when describing natural and synthetic chemical structures[3]. However, chemical complexity can be conceptualized in a more rigorous way

[1] *e.g.* Conrad and Nealson, 2001, *Astrobiology*; Baross et al, 2007, The Limits of Organic Life in Planetary Systems; Schulze-Makuch and Irwin, 2008, Life in the universe: expectations and constraints; Scharf et al., 2015, *Astrobiology*

[2] Goesmann et al., 2017, *Astrobiology*

[3] *e.g*. Nicolaou et al., 2012, *Chem Soc Rev*; Ertl and Schuffenhauer, 2009, *J Cheminform*; Bickerton et al., 2012, *Nature Chemistry*

if mapped directly to an increase in the number of components in a system and versatility of their interactions, and if it reflects structural features, including branching, cyclicity, multiple edges, and heteroatoms.

Recent work at the University of Glasgow has utilized graph theory to understand molecular structure, therefore serving as a measure of intrinsic complexity, rather than being context dependent[4]. By encoding a graph and enumerating graph features like subgraphs or walks, generational algorithms can be used to count the operations needed to build complexity graphs out of simpler graphs, thereby computing a Pathway Complexity Index (MCI) for any molecule (see **Figure 1**). This work is based on the thesis that the ability of living systems to replicate and evolve allows for the generation of complex molecules, such as metabolites and co-factors, which would be highly unlikely to form in any significant quantity in the absence of biology. Work remains to be done in benchmarking the algorithm, exploring chemical space, and fragmentation mapping with flight capable ion traps, but repeated measurements above a certain complexity carry the promise of agnostically detecting whether molecules formed as the result of biology.

Without making assumptions about the chemical structures of molecules, recently published research suggests there may be a threshold beyond which complex molecules are unlikely to form without supporting biological machinery.

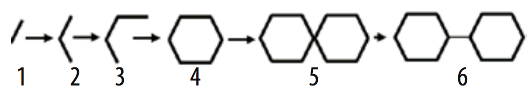

Figure 1: *What is the simplest way to construct a molecule from its parts, accounting for the simplifying feature of duplication? As an example, an algorithm can be used to break biphenyl into a six-step construction process, therefore assigning an MCI of 6. Among natural products, synthetic drugs, amino acids, metabolites, and other chemical compounds, there appears to be a MCI threshold of 15, above which no molecules tested thus far have an abiotic origin.*

Along similar lines, sequencing technologies have been developed by NASA's ASTID, MATISSE, and COLD-Tech instrument development programs as a way to search for nucleic acids based on a shared ancestry hypothesis and monitor terrestrial contamination[5]. Rapid advances in miniaturization have led to stand-alone sequencers, like the Oxford Nanopore MinION, which was recently demonstrated on the International Space Station[6].

While this approach is specific to a particular class of molecules (nucleic acids, including those with nonstandard bases), work at Georgetown University, the University of Texas at Austin, and NASA Goddard Space Flight Center has begun to lay the foundation to harness the power of sequencing to explore sample complexity, regardless of whether life is based on nucleic acids. This concept, as detailed in a forthcoming paper in *Astrobiology*[7], builds on the fact that oligonucleotides naturally form secondary and tertiary structures that can have affinity and specificity for a variety of molecules, from peptides and proteins[8], to a wide variety of small organic molecules[9], to inorganics such as mineral surfaces[10] and individual metals[11]. Binding

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[4] Marshall *et al*., 2018, *Philosophical Transactions of the Royal Society A*
[5] Carr et al., 2016, *IEEE Aerospace Conference*; Mojarro et al., 2016, *LPSC*; Bywaters et al., 2017, *AbSciCon*
[6] Castro-Wallace *et al.,* 2017, *Scientific Reports*
[7] Johnson et al., in press, *Astrobiology*
[8] Sun and Zu, 2015, *Molecules*

patterns of nucleic acids, independent of their biological function, can thereby be used to probe and report on any chemical environment, opening up a new way to detect agnostic biosignatures.

DNA sequences as short as 15 nucleotides in length (but more commonly 30-80 nucleotides in length) can form complex structures that, like antibodies, will bind to analytes, from simple inorganics or minerals to highly complicated cell surfaces[12] (See **Figure 2**).

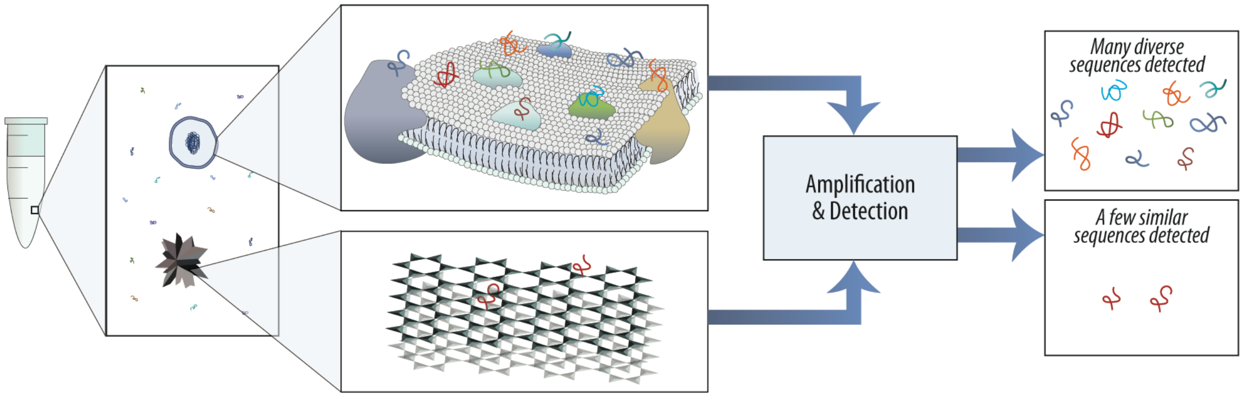

Figure 2: *A new concept for life detection harnesses the power of DNA sequencing, but not to look for nucleic acid based life. 1) DNA strands are mixed with samples. 2) Many diverse folded oligonucleotides will bind to a complex surface, such as a cell membrane whereas far fewer will bind to a simple, repeating, inorganic crystalline structure. 3) Bound sequences can be amplified and sequenced, revealing the diversity of binding sites within a sample. No prior knowledge of the surface attributes or about the 3D structures of the binding nucleic acids is required, thereby enabling an extension beyond terrestrial conceptions of what life may look like.*

By accumulating large numbers of binding sequences that reflect different compounds in a mixture, statistical data analyses of oligonucleotide sequences and sequence counts enable patterns associated with increasing levels of complexity to be analyzed. This pattern recognition, known as "chemometrics," represents a set of protocols that can be applied to find patterns in chemical data sets[13], which in turn can be used to fingerprint nonterran biosignatures.

> A newly developed approach could distinguish samples with chemistries suggestive of biology—to "read" patterns of molecules, for example arising from the vast amount of information stored on the surface of a primitive microbial cell, and to do it with great sensitivity.

Additional work is required to hone the chemical assays and refine the chemometrics, but without presupposing any particular molecular framework, this life detection approach could be used from Mars to the far reaches of the solar system, all within the framework of a miniaturized chip drawing little heat and power. While the amount of biomass produced on Ocean Worlds may be limited[14], utilizing the power of PCR, this technique could be capable of amplifying the signal associated with an exceedingly small input. Further refinements in NextGen chemometrics may

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[12] *e.g.* Jayasena, 1999, *Clinical Chemistry*

[13] *e.g.* Goodwin et al., 2015, *Angewandte Chemie*; Hughes et al., 2008, *Chemistry–A European Journal*; Pai and Ellington, 2009, Biosensors and Biodetection; Stewart et al., 2011, *Chembiochem*; Umali and Anslyn, 2010, *Current opinion in chemical biology*; Wright et al., 2005, *Angewandte Chemie*; Zamora-Olivares et al., 2014, *Angewandte Chemie*

[14] McCollum, 1999, *JGR*

be able to not only generate the binding "fingerprint" of a surface but also reveal associated physical structures.

Several other agnostic biosignatures have been surmised that could take advantage of high heritage instrumentation, including non-chemical methods. For instance, holographic microscopy with computational modeling of non-random motion to identify isolated structures, including those capable of meaningful movement and/or responding to taxis, could also serve as a non-Earth-centric approach (for more detail, see the white paper submitted by Jay Nadeau and colleagues).

Pursuing New Leads

Other concepts remain at a nascent stage. While biological phenomena, from biomolecular production to growth and biosynthesis, have indelible "biosignatures," it is also true that these compounds and processes are, in essence, well-coordinated chemical reactions. Metabolically active organisms, by necessity, maintain themselves at chemical disequilibrium from the environment. This disequilibrium can be detected and the biogenicity of this signal assessed. Redox reactions are typical mechanisms for terran organisms to create energy and terran life can use organic carbon as a reductant and a diversity of soluble oxidants including oxygen, nitrate, sulfate and carbon dioxide. An agnostic approach to life detection would not limit bioelectrochemical observations to just these compound pairs though. Rather, disequilibrium redox chemistries that are inconsistent with abiotic redox reactions could be used as an indicator of active metabolism.

Many microbes can utilize an active anode as an electron acceptor in the same way as they utilize insoluble Fe(III) oxides as an electron acceptor during respiration. Because the response measured from those electrons being transferred from organic substrates is characteristically different and more sustained than the response measured from electrons generated by abiotic oxidation, this signal could be used as an agnostic biosignature.

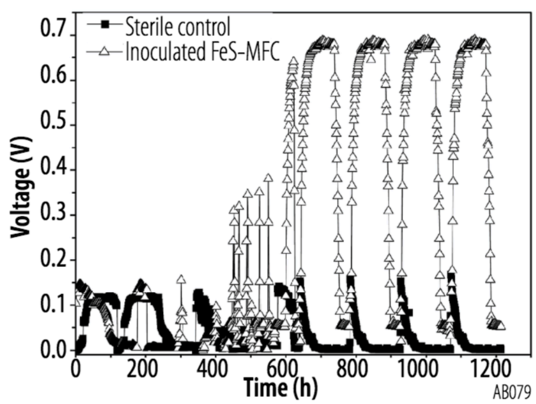

Figure 3. *This experiment (from Nie et al., 2015) illustrates how abiotic and biological signals are apparent even in simple cases.*

An illustration of these observations are the results reported by Nie et al.[15] (**Figure 3**). These simple experiments "fed" microbial communities iron sulfide mine tailings and found a marked and sustained increase in voltage (and thus net coulombs recovered) in the reactor with a microbial community compared to a sterile control. These reactions can also be divorced from observations of cellular activity. Microbial extracellular electron transfer (EET) has been observed in terran life, where organic redox-active molecules shuttle electrons to insoluble mineral oxides[16]. Assuming these reactions are the basis of energy production for life in any environment, the subsequent development of bioelectrochemical detection instruments offer a new way to study physiology in nature. These methods and technologies can be used in remote habitats (both well-established extraterrestrial analogs and

[15] Nie et al., 2015, *RSC Advances*

[16] Lies *et al.*, 2005, *AEM*; Watanabe *et al.*, 2009, *Current Opinion in Biotechnology*

recently discovered habitats that are of ocean worlds relevance) to produce a robust set of electrochemical criteria that can be used to agnostically differentiate between biological and abiotic electrochemical reactions.

Probabilistic Approaches to Data Analysis

While it is necessary to broaden our scope and design inclusive life detection strategies, these approaches may be less definitive than, say, uncovering a hopane or DNA sequence. A data interpretation scheme that considers expectations and likelihoods and establishes critical thresholds for life detection based upon probabilistic models is thereby key.

> Life detection may best be viewed along a spectrum of certainty, as opposed to a binary "life" versus "no life" model.

Modern space missions typically include packages of instruments, results of which should be considered in tandem. Multiple inputs from multiple types of measurements can be combined to assess certainty. It may be that no single signature will serve as unequivocal evidence for extraterrestrial life, but rather that data from a variety of approaches will be required. For instance, a Bayesian network for which the output is the probability there is a biosignature given the measurement data (*i.e.,* P(biosignature | Data) can be utilized to assess the probability of life, and thus convert measurements into likelihoods and thresholds. The results of this data treatment would enable the community to make recommendations for particular suites of techniques best suited for particular types of samples. A Bayesian net could help identify complementary analyses without redundancy. Simultaneous analysis of multiple sources of data could lead to useful higher order likelihoods.

Expectations for abiotic signals can be set by developing challenging null models. For instance, models of nonterran physical and physiological environments can generate a large space of synthetic data representing a wide variety of possibilities for life. These models, which do not pre-suppose terran chemistry, heritage, or physiology, can help the community build "life-relevant" expectations for our collected data. Theoretical models can also inform the limits of biology in foreign environments, anticipate necessary trade-offs indicative of alternate life strategies, and help us to understand minimum sample sizes necessary to provide robust statistical analysis for the results. A theoretical approach that focuses on combining inclusive principles with physical and chemical laws to define feasibility regimes. Required sample sizes could be estimated by "sampling" observations from an artificial "universe" where probabilities are known, and an inference using a Bayes Net could be generated to see how close they come to the probabilities in the model. Studies that carefully consider the abiotic mimics of biosignatures and what tools and metrics can distinguish them from life are also of critical importance.

Conclusion

Deeper in Solar System, the likelihood that life shares a common heritage with Earth diminishes. Thereby, a fundamental scientific question for the astrobiology community is how to develop life detection approaches that inform our search for life without presupposing any particular molecular framework. Agnostic biosignature detection concepts need to be advanced individually but also joined in a unified data interpretation program informed by probabilistic models. International partnerships among teams of biologists and chemists, computer scientists and mathematicians, as well as planetary scientists and veteran instrument scientists will help to ensure the astrobiology community most effectively realizes this promising research goal.

Venus: The Making of an Uninhabitable World

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White paper submitted in response to the solicitation of feedback for the "Astrobiology Science Strategy for the Search for Life in the Universe" by the National Academy of Sciences.

Abstract

The goals of the astrobiology community are focussed on developing a framework for the detection of biosignatures, or evidence thereof, on objects inside and outside of our solar system. A fundamental aspect of understanding the limits of habitable environments and detectable signatures is the study of where the boundaries of such environments can occur. Thus, the need to study the creation, evolution, and frequency of hostile environments for habitability is an integral part of the astrobiology story. These provide the opportunity to understand the bifurcation, between habitable and uninhabitable. The archetype of such a planet is the Earth's sister planet, Venus, and provides a unique opportunity to explore the processes that created a completely uninhabitable environment and thus define the conditions that can rule out bio-related signatures. We advocate a continued comprehensive study of our sister planet, including models of early atmospheres, compositional abundances, and Venus-analog frequency analysis from current and future exoplanet data. Moreover, new missions to Venus to provide in-situ data are necessary.

1. Studying the Venusian Environment is Imperative for Astrobiology

The prime focus of astrobiology research is the search for life elsewhere in the universe, and this proceeds with the pragmatic methodology of looking for water and Earth-like conditions. In our solar system, Venus is the most Earth-like planet, yet at some point in planetary history there was a bifurcation between the two: Earth has been continually habitable since the end-Hadean, whereas Venus became uninhabitable. Indeed, Venus is the type-planet for a world that has transitioned from habitable and Earth-like conditions, through the inner edge of the Habitable Zone (HZ); thus it provides a natural laboratory to study the evolution of habitability. If we seek to understand habitability, proper understanding of the boundaries of the HZ are necessary: further study and development of our understanding of the evolution of Venus' environment is imperative. Furthermore, current and near-future exoplanet detection missions are biased towards close-in planets (see Section 4), so the most suitable targets for the *James Webb Space Telescope (JWST)* are more likely to be Venus-like planets than Earth-like planets. Incomplete understanding of the evolution of Venus' atmosphere and its present state will hinder the interpretation of these observations, motivating urgent further study.

2. The Current Venus: An Uninhabitable Hellscape

Venus could be considered an "Earth-like" planet, because it has a similar size and bulk composition. However, it has a 92 bar atmosphere consisting 96.5% CO_2 and 3.5% N_2, and a surface temperature of 735 K. Venus' atmosphere is explained by a runaway greenhouse having occurred in the past (Walker 1975), when insolation exceeded the limit on outgoing thermal radiation from a moist atmosphere (Komabayashi 1967; Ingersoll 1969; Nakajima et al. 1992; Goldblatt & Watson 2012; Goldblatt et al. 2013), evaporating the ocean. It is unclear whether the ocean condensed, then later evaporated, or never condensed after accretion (Hamano et al. 2013, H2013). In either case, water loss by hydrogen escape followed, evident in high D/H relative to

Earth (Donahue 1982). Complete water loss would take a few hundred million years (Watson et al. 1982), but may have been throttled by oxygen accumulation (Wordsworth & Pierrehumbert 2014). Notably, massive water loss during a runaway greenhouse has been suggested as producing substantial O_2 in exoplanet atmospheres (Luger & Barnes 2015), but Venus serves as a counter-example to this. Hydration of surface rocks (Matsui & Abe 1986) or top-of-atmosphere loss processes (Chassefière 1997; Collinson et al. 2016) are potential sinks for water. Thus, Venus is an ideal laboratory to test hypotheses of abiotic oxygen loss processes.

Cloud-top variations of SO_2 have been observed across several decades from *Pioneer Venus* to *Venus Express* observations (Marcq et al. 2012), implying a long-term atmospheric cycling mechanism, or possibly to injections via volcanism. Recently, nine emissivity anomalies due to compositional differences were identified by the VEx Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) aboard *Venux Express* as sites of potentially recent volcanism (Smrekar et al. 2010, S2010). There are purported lava flows associated with these anomalies estimated to be 2.5 million years old at most, and more likely to be as young as 250,000 years old or less (S2010) based on expected weathering rates of freshly emplaced basalts. The emissivity anomalies sit atop regions of thin, elastic lithosphere according to *Magellan* gravity data, strengthening the volcanism interpretation. In 2015, additional evidence for active volcanism on Venus was uncovered with a new analysis of *Venus Express*' Venus Monitoring Camera (VMC) data. Four temporally variable surface hotspots were discovered at the Ganiki Chasma rift zone near volcanoes Ozza Mons and Maat Mons (Shalygin et al., 2015), suggestive of present volcanic activity. However, interpreting these types of observations from above the cloud layer correctly is a challenge. The scattering footprint of radiation from the Venus surface escaping through the cloud deck is about 100 km^2, so smaller areas of increased thermal emission are smeared out.

3. Critical questions: The Need to Understand Earth's Twin

Many significant questions remain on the current state of Venus, suggesting major gaps in our understanding of the evolution of silicate planets, including the future evolution of Earth. Major outstanding questions include:

- Did Venus have a habitable period (e.g. Way et al. 2016)? That is, did Venus ever cool from a syn-accretionary runaway greenhouse?
- Where did the water go? Was hydrogen loss and abiotic oxygen production rampant, or did surface hydration dominate?
- What has the history of tectonics, volatile cycling, and volcanic resurfacing been? When did Venus enter its present stagnant-lid regime? Does any subduction occur today?

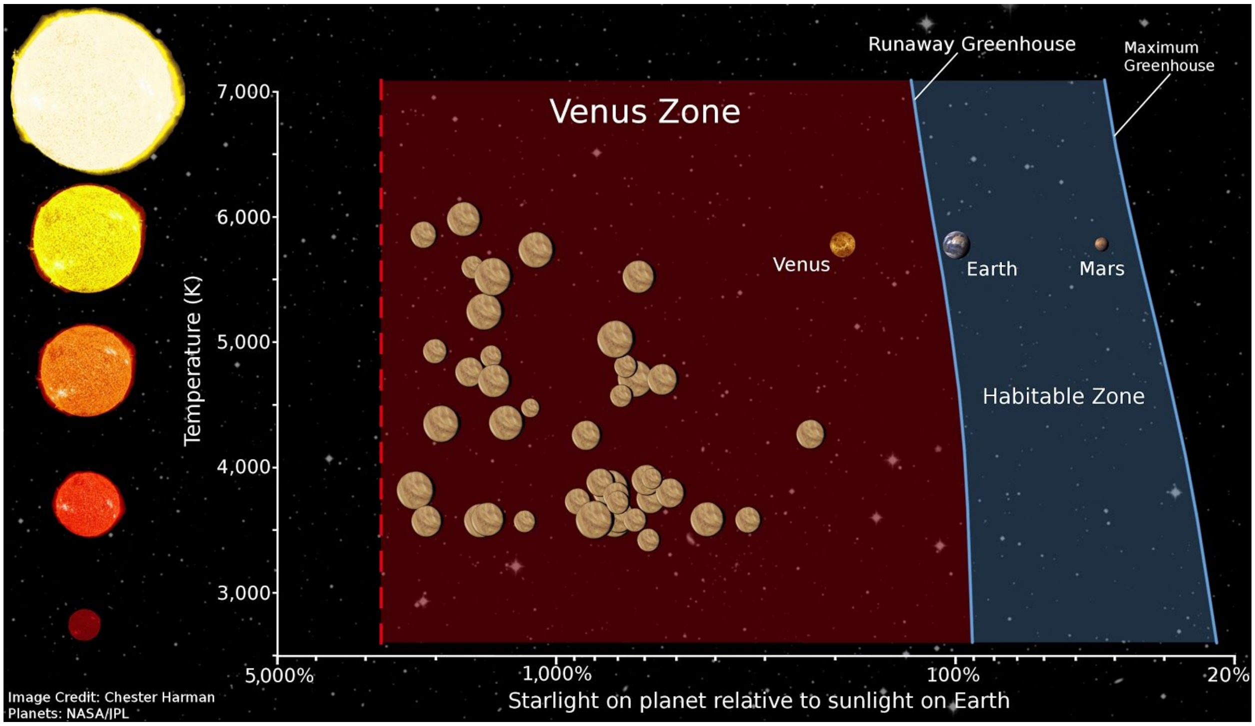
Venus accounts for 40% of the mass of terrestrial planets in our Solar system, yet even fundamental parameters such as the relative size of its core to mantle are unknown. As we expand the scope of planetary science to include those planets around other stars, the lack of measurements for basic planetary properties such as moment of inertia, core-size and state, seismic velocity and density variations with depth, and thermal profile for Venus hinders our ability to compare the potential uniqueness of the Earth and our Solar System to other planetary systems. Furthermore, the relative abundances of Venus' refractory elements can greatly inform the degree of mixing of planetesimals within this critical zone in the disk: where terrestrial planet are formed. If these relative refractory ratios are reflected in the size of its core, we gain by constraining even this simple structural parameter of Venus, a key benchmark in future studies of how our Solar system formed. This, in turn, will greatly aid in our studies of exoplanets, where stellar composition may set the initial compositional gradient of planetesimals within the disk but degree of mixing remains an elusive, unconstrained parameter.

4. A Plethora of Venus Analogs

The inner and outer boundaries of the HZ for various main sequence stars have been estimated using climate models, such as those by Kasting et al. (1993), and more recently by Kopparapu et al. (2013, 2014). An important aspect of these HZ calculations is that they provide a means to estimate the fraction of stars with Earth-size planets in the HZ, or eta-Earth. Much of the recent calculations of eta-Earth utilize *Kepler* results since these provide a large sample of terrestrial size objects from which to perform meaningful statistical analyses (Dressing & Charbonneau 2013, 2015; Kopparapu 2013; Petigura et al. 2013).

The transit method has a dramatic bias towards the detection of planets which are closer to the host star than farther away (Kane & von Braun 2008). Additionally, a shorter orbital period will result in an increased signal-to-noise (S/N) of the transit signature due to the increased number of transits observed within a given timeframe. The consequence of this is that *Kepler* has preferentially detected planets interior to the HZ which are therefore more likely to be potential Venus analogs than Earth analogs. Since the divergence of the Earth/Venusian atmospheric evolutions is a critical component for understanding Earth's habitability, the frequency of Venus analogs (eta-Venus) is also important to quantify.

Kane et al. (2014) defined the "Venus Zone" (VZ) as a target selection tool to identify terrestrial planets where the atmosphere could potentially be pushed into a runaway greenhouse producing surface conditions similar to those found on Venus. The below figure shows the VZ (red) and HZ (blue) for stars of different temperatures. The outer boundary of the VZ is the "Runaway Greenhouse" line which is calculated using climate models of Earth's atmosphere. The inner boundary (red dashed line) is estimated based on where the stellar radiation from the star would cause complete atmospheric erosion. The pictures of Venus shown in this region represent planet candidates detected by *Kepler*. Kane et al. (2014) calculated an occurrence rate of VZ terrestrial planets as 32% for low-mass stars and 45% for Sun-like stars. Note however that, like the HZ, the boundaries of the VZ should be considered a testable hypothesis since runaway greenhouse could occur beyond the calculated boundary (H2013, Foley 2015).



The prevalence of Venus analogs will continue to be relevant in the era of the *Transiting Exoplanet Survey Satellite (TESS)* mission, as hundreds of terrestrial planets orbiting bright host stars are expected to be detected (Sullivan et al. 2015). These will provide key opportunities for transmission spectroscopy follow-up observations using *JWST*, amongst other facilities. Such observations capable of identifying key atmospheric abundances for terrestrial planets will face the challenge of distinguishing between possible Venus and Earth-like surface conditions. Discerning the actual occurrence of Venus analogs will help us to decode why the atmosphere of Venus so radically diverged from its sister planet, Earth.

5. The Path Forward

The only in-situ terrestrial planet data available to us are here in our solar system. Thus, it is imperative that we gather improved information on Venus to aid in modeling both habitability and planetary interiors. The greatest advances in studies of Venus will come from a better understanding of the top-level questions described in Section 3 for which a series of missions - at multiple cost scales - could address parts thereof. Atmospheric modeling of exoplanets is of critical importance and an improved sampling of pressure, temperature, composition, and dynamics of the Venusian atmosphere as a function latitude would aid enormously in our ability to study exoplanetary atmospheres. In particular, new direct measurements of D/H within and below the clouds are needed to better constrain the volume of water present in Venus' history. Combined with D/H, isotopic measurements in the atmosphere would yield insights into the origins and fate of the Venusian atmosphere. A descent probe or lander to the surface (as a Discovery- or New Frontiers-class mission, or as part of a larger flagship mission) would make significant new measurements of atmospheric structure and D/H, as well as noble gas abundances and isotopic ratios. Such a mission could also provide first-ever measurements of the deepest atmosphere. Aerial platforms, such as balloons complement the vertical probe profiles by providing 2-D coverage of cloud region. These fundamental measurements would stimulate progress on multiple fronts, and vastly improve our understanding of both modern Venus and the transition of Venus to its modern state. Inclusion of a seismometer on future landers or long-term orbiters to measure moment of inertia, will provide new knowledge about the Venusian interior that is a critical, and necessary, step to expand our inferred knowledge of *any* exoplanet system.

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Exo-Life Finder (ELF):
A Hybrid Optical Telescope for Imaging Exo-Earths

Astrobiology Science Strategy for the Search for Life in the Universe

National Academies of Sciences, Engineering, and Medicine

White Paper, January 2018

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Summary

Finding and studying life in the Universe beyond the solar system is an ultimate goal of astrobiology. This objective requires dedicated discovery technology. **Here we describe an opportunity to discover extrasolar life (exolife) within 10 years.** Our paper presents a new concept for a hybrid telescope-interferometer, the Exo-Life Finder (ELF), that can directly image Earth-size water-bearing planets in the optical and IR within tens of light years from the Sun. High-contrast direct imaging of exo-Earths is a holy grail of optical-IR remote sensing that will allow the measurement of biosignatures and exoplanetary reflected light. Inversions of such light curves will yield wavelength-dependent albedo surface maps of potentially unambiguous signals of exoplanetary life, from single-cell photosynthetic organisms to advanced life-forms. Such data may even provide technomarkers of civilizations, through heat-island signatures or artificial mega-structures on the planetary surface and near-space. The ELF ground-based telescope consists of nine to twenty-five large (4-8m) off-axis telescopes assembled on a common pointing structure. The primary mirror segments have identical off-axis parabolic shapes, and are served by corresponding adaptive secondary mirrors, each creating a diffraction-limited image with high-accuracy wavefront control. The synthesized point-spread-function (PSF) created by properly phasing the ELF segments can produce a 10^{-7} contrast dark spot that can be moved within the field-of-view (FOV) by modifying segment phases. ELF's narrow FOV and hybrid technology reduce its cost by a factor of 10 compared to general-purpose extremely large Keck-era telescopes. Current ELF concept studies, involving expert engineering groups, like Dynamic Structures (currently designing other Extremely Large Telescopes 'ELTs'), suggest that ELF can be built within 7 years. **On a cost scale of \$100M, or less than the cost of a small NASA mission, ELF could yield a statistically valuable census of life on nearby exoplanets.** As a dedicated telescope for detailed exoplanet characterization, its first targets will include Proxima b, Ross 128 b, Alpha Cen A and B, as well as dozens of stars and planetary systems in the solar neighborhood.

1. Why ELF?

Currently planned ELTs are optimized for relatively wide-field general astronomy and will not necessarily address many exoplanetary science goals. We believe the rapidly growing field of exoplanetary science justifies a dedicated narrow-FOV instrument that is capable of high-contrast direct imaging in the optical and infrared. **ELF is a hybrid interferometric telescope, that will be sensitive to exolife biosignatures from many near-by extrasolar planets.** It will image Earth-size planets and acquire high signal-to-noise ratio (SNR) continuous reflected light curves at 0.3–5μm within the next decade.

The integration time needed at fixed SNR in direct exoplanet photometry scales faster than D^{-4} (where D is telescope aperture) and depends critically on exquisite wavefront control (reaching rms wavefront errors of a few nanometers) for high contrast. As a narrow-FOV optic ELF may combine interferometric concepts with a relatively "floppy" mechanical structure to significantly decrease the moving mass and cost per m^2 of light collecting aperture while realizing extremely high photometric dynamic range. These ELF advantages make comparable-aperture space-based systems non-competitive in both cost and time-to-realization.

An ELF with an effective aperture of at least 20 m will fulfill an astrobiology strategic goal to sensitively search for life beyond the Solar system. It will, for example, allow detailed exoplanet albedo maps to be inferred from light curves in various spectral bands. This dedicated telescope may also "see" exo-Earth oceans, continents, and colonies of surface life like extremophiles and vegetation as well as deserts, volcanos, polar caps (see Fig. 1), and even civilization heat-islands and artificial megastructures on the surface and in the near-exoplanetary space [1,2]. It may detect O_2, O_3, CO_2, CH_4, H_2O and other biosignature gases and habitability markers, disequilibrium biosignature gas pairs, organic haze in anoxic atmospheres [3], and photosynthetic and non-photosynthetic pigments [4,5].

ELF will be capable of characterizing atmospheres and surface bulk composition of the nearest m-dwarf exoplanet Proxima b [6], and over a period of a few months it will map its surface (and/or clouds) which may harbor life. Obtaining surface maps in multiple wavelengths will provide spatially resolved spectra of surface features that will allow for geologic and biologic studies of the planetary surface (Fig. 1). ELF will easily reveal and characterize Earth-size (and larger) planets in the Alpha Centauri A and B system, thus expanding the number of nearest exoplanets for detailed studies. Finally, ELF will deliver time series of albedo maps of all exoplanets (from Earth- to Jupiter-size) within 25 light years (up to $V=13^m$, Fig. 2). It will create the first complete census of exo-life on nearby exoplanets and will allow weather, seasons, geological and biological activity studies on a meaningful sample of exoplanets.

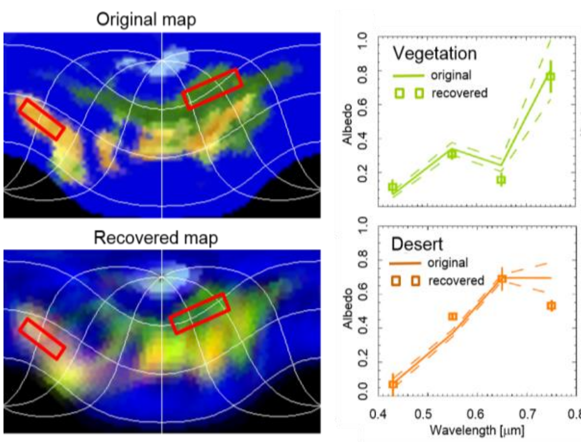

Figure 1. Example of an exo-Earth with an ice polar cap, ocean, and continents with deserts and vegetation. An Earth-like map is used to simulate reflected light curves in four passbands within 0.4–0.8 μm. The recovered map is a three-color image inferred using light-curve inversion. Spectra of two surface patches reveal vegetation "red-edge" and a typical desert composition (on the right). [1].

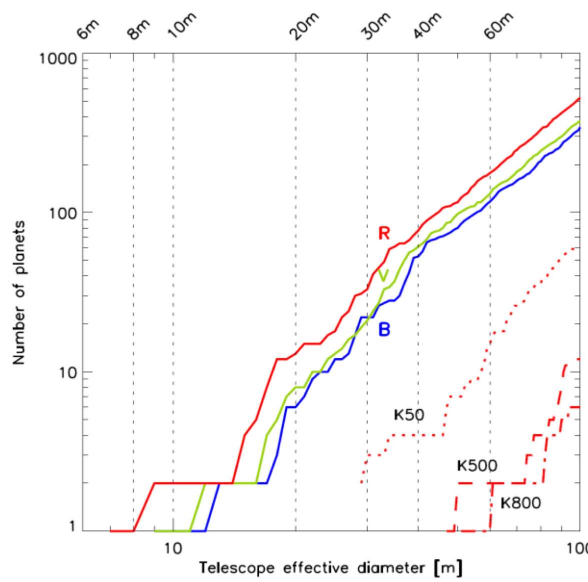

Figure 2. Number of detectable exoplanets (SNR≥5, $V \leq 13^m$, 4h exposure) depending on the low-scattered-light hybrid telescope aperture in BVR bands (solid lines) and comparable estimates for a Keck-like telescope (K50-800) with 50-800 segments.

2. ELF Design Concepts

The technology for building a powerful exoplanet "imager" that exceeds the capabilities of Keck-era telescopes already exists. With minimal additional development, we can force the cost per aperture area down by an order of magnitude, so that an ELF could be built for less than the cost of a small NASA explorer mission. Such a ground-based telescope for direct imaging exoplanet studies depends on five design principles [7,8]: 1) the effective aperture should be large, 2) the subapertures should also be as large as practical while accounting for wavefront and diffraction control, 3) the moving mass must be minimized, 4) there must always be a relatively bright star in the FOV, so that wavefront control for phasing and adaptive optics can be performed accurately, 5) the synthesized optical PSF should yield a practical diffraction minimum in the FOV, so that the effect of residual wavefront errors does not spoil high dynamic range photometry. These principles and the ELF concept naturally lead to a "scalable" optical system design.

ELF's intrinsically narrow FOV and its fundamental requirement for a bright central star allow an optical system that is similar to the phased-array radars that create "synthetic" PSFs, but in this case the phasing and wavefront control are achieved with a closed-loop system that uses the exoplanet's near-point-like host star as a guide. Many elements of this strategy have been developed by the "Colossus Group" and more recently by the PLANETS Foundation [7–12]. The primary conclusions relevant for ELF are as follows:

1) With additive (3D printing) technologies we can create an active structure on smooth fire-polished window glass that creates "stiffness" with considerably less mass than the glass-steel backing structure of, e.g., Keck-era mirror segments [11]. Current glass technologies allow patent-pending "live-mirrors" (Fig. 3) to be as large as 8m in size with an area-mass-density that approaches 1/10th of Keck-era mirrors. These optical elements could be constructed at the telescope site and would never undergo abrasive polishing.

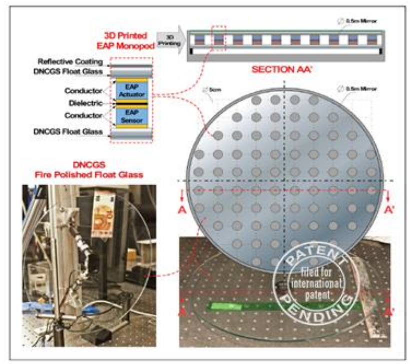

Figure 3. Live-Mirror proof-of-concept (0.5m) developed by the PLANETS foundation.

2) A single moving mass for the large diffraction-limited subapertures need not be as stiff as current ELTs, if each subaperture comes from a common parent parabolic optic shape and each independent subaperture secondary mirror provides the required adaptive and active tip/tilt/phase control. In this active/adaptive/high-Strehl telescope it is wasteful to use the mass budget to build an optical system that is "stiffer" than the intrinsic atmospheric and thermal wavefront errors that will be corrected by the active/adaptive control.
3) We have demonstrated how the necessary subaperture phase information can be efficiently recovered from the common-path full-aperture final image.
4) The moving optical support structure mass can be further minimized with a "bicycle wheel-like" structure that combines pre-tensional and compressional mechanical elements.

All of these features lead to a new type of extremely large aperture telescope that has extraordinary wavefront control and a small moving mass in comparison to Keck-era optical systems.

2.1. Optical and mechanical designs

As an example, the ELF optical design in Fig. 4 combines 16 eight meter diameter off-axis "live-mirror" parabolic segments with 16 elliptical secondaries in a basic Gregorian configuration. The subapertures are constructed from active "live-mirror" 6mm thick smooth no-polish glass. Each corresponding temporally fast adaptive secondary optic is about 15cm across and includes tip/tilt/piston control. The Gregorian focus provides additional articulated wavefront measurements for the temporally slow active shape control needed for the primary subapertures. The full optical system creates a final diffraction-limited Gregorian focus near the vertex of the parent optic. The narrow FOV allows for a very fast optical system (with a focal ratio less than 0.5) and a correspondingly small enclosed volume of the system moving mass.

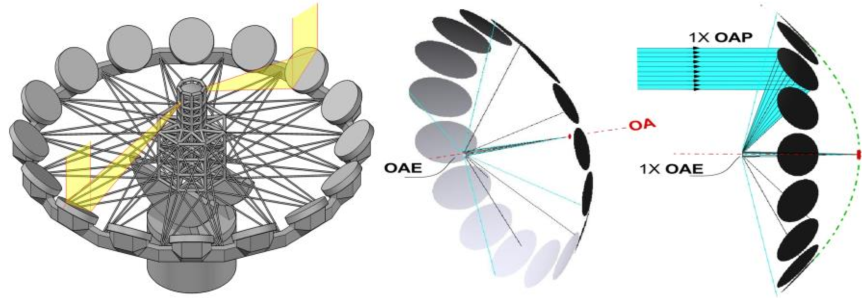

Figure 4. ELF Gregorian-focus off-axis parabolic optical configuration.

A mass-efficient mechanical design allows a 45 degrees zenith pointing distance and uses a "bicycle wheel" pretensioned moving support structure for the optical payload. Fig. 5 illustrates two concepts, one utilizes a wind fence enclosure and a telescoping central tower that allows the optical system to be lowered into a stowed position, while the second shows how separate retractable subaperture enclosures could be implemented.

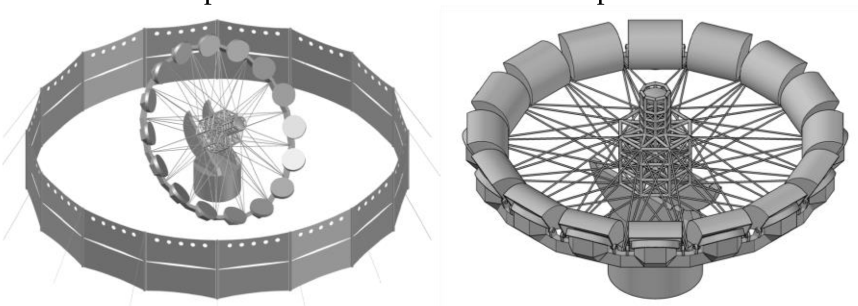

Figure 5. ELF Mechanical enclosure concepts: wind fence (left) and mirror covers (right).

2.2. Wavefront control and coronagraphy

ELF is fundamentally an adaptive/active telescope – it relies on photons from the exoplanet host star to create a high-strehl diffraction-limited PSF. Residual wavefront errors, larger than the fundamental wavefront measurement accuracy allowed by the stellar photon flux, are inevitable but their deleterious effects are minimized by an optical system with a diffraction pattern that has a dark hole in the FOV where we measure the exoplanet reflected light. ELF does not depend on a post-focus coronagraph since its synthesized "coronagraphic" PSF is created by the telescope itself. This has the important well-known advantage that the system PSF, that modulates residual wavefront errors, attenuates the photometry-limiting speckle noise near the exoplanet (i.e. "speckle-pinning" [12]). Figure 6 shows how a fixed phase introduced in each subaperture (by displacing the agile elliptical secondaries) can create a diffracted dark spot, and how the residual wavefront phase-induced intensity noise is correspondingly attenuated in the dark spot.

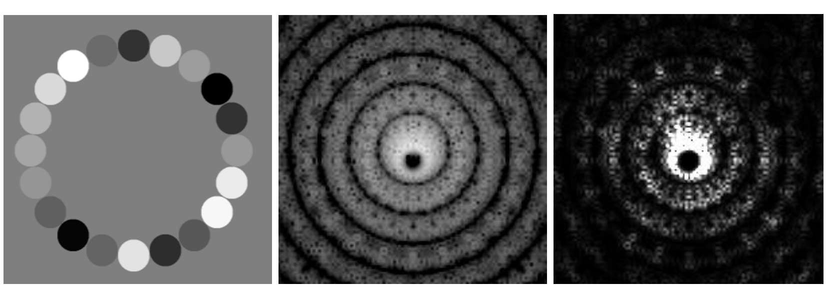

Figure 6. *Left:* Subaperture darkspot phase solution represented on 360deg linear greyscale. *Center:* PSF on log-scale 8 decades. *Right:* RMS speckle noise on log-scale 6 decades.

3. The ELF Proposal

The development of the ELF and the related Colossus and PLANETS telescopes, so far has relied on private and institutional support from Dynamic Structures Ltd., MorphOptic Inc., PLANETS Foundation, KIS, Tohoku University, CRAL/CNRS/Lyon University, and recently from the SETI institute. The ELF working group includes more than two dozen scientists and engineers. With this brief paper we seek public support for a fully vetted construction proposal over an 18-month period. The needed technology demonstrations and a detailed engineering design could be completed within a $1.8M budget, possibly leveraged by the partner institutions, scientists, engineers, and entrepreneurs included here.

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Habitability and Biosignatures

Astrobiology Science Strategy White Paper

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As a one of the authors, this astrobiology science strategy white paper offers good review chance on what has happened in the field after the completion of the NASA Astrobiology Strategy in 2014. However, as astrobiology is an Interdisciplinary research field, it is difficult to keep up with all the progress in related sciences. Therefore, only a few research areas are reviewed here.

It seems, that there has been progress in many areas of research included in the NASA Astrobiology Strategy, but many questions remain open. The reason for this is that some of these questions are fundamental (the origin of life), or that we are lacking adequate research instruments or methods (e.g. low sensitivity of telescopes or access to planetary locations).

In the NASA Astrobiology Strategy there are listed areas of research within each topic. I will review here only one of these:

5. Identifying, exploring, and characterizing environments for habitability and biosignatures.

- How can we assess habitability on different scales?

  The NASA Astrobiology Strategy identifies planetary system, planet-wide, regional, local, subsurface, and temporal scales that can be used to assess habitability. We can see general progress in all of these scales, as instruments and detection methods get better and new planetary missions become available. We can identify three main targets of habitability assessment: Mars, icy moons, and exoplanets. Ongoing and future missions to Mars extend our access to different locations. Planned mission to Europa and other moons of Jupiter will do the same for these potential ocean worlds.

- How can we enhance the utility of biosignatures to search for life in the Solar System and beyond?

  We can apply the previous comment here: there is a steady progress of instruments and detection methods also for biosignatures.

- How can we identify habitable environments and search for life within the Solar System?

  There is intense research on Earth analogs (e.g. caves, permafrost and hydrothermal vents) and extremophiles (e.g. EXPOSE experiment in the ISS). Together this research will yield information about the limits of life. Mars is active target of astrobiological research, both on Earth analogs, simulation environments, and is-situ (e.g. MSL rover and ESA's ExoMars TGO). Also, forthcoming Mars 2020 and ESA's ExoMars rover are primarily astrobiological missions, including multiple instruments for habitability assessment and biosignature detection. Especially ExoMars rover's drill will be capable to access subsurface locations down to 2 meters below. Eventually there will be human Mars exploration, which will give us more versatile access to potential biosignatures. Cassini (1997-2017) delivered us unparalleled amount of information about Enceladus and Titan, the prime astrobiology targets in Saturnian system, and the analysis of the results is still going on. New astrobiology missions to Jovian system are been developed based on legacy previous missions (Europa Clipper and ESA's JUICE missions).

- How can we identify habitable planets and search for life beyond the Solar System?

  Exoplanet research is one of the most advancing research areas. New exoplanets have been detected on regular basis. One of the key detections during the last years is the

TRAPPIS-1 system, with seven planets in the habitable zone. However, what we really need is a detection of atmospheric spectra that includes biosignature gases, such as oxygen, ozone, methane, nitrous oxide etc. Forthcoming space telescopes will be capable of detecting such spectra from planets around nearby stars. We should also keep our eyes open for anomalies that could be technosignatures of advanced civilizations.

From the notes above, we can point few key scientific questions and technology challenges in these research areas: How to identify habitable environments within our Solar System and beyond? These environments include elusive subsurface locations in Mars and in icy moons, and distant point like targets around other stars. Even more difficult is to detect potential biosignatures in these targets.

However, these targets are the most promising key research goals in the field of the search for signs of life within the next 20 years. There will be multiple exoplanet detection instruments: TESS, JWST, CHEOPS, PLATO, WFIRTS, and terrestrial telescopes. It is still unclear what kind of biosignature is needed for confirmation for sign of life in exoplanet. The exploration of Mars will bloom: Mars 2020 and ExoMars rovers, and the potential human Mars exploration will give us unprecedented access to different locations in Mars. Also, the exploration of the icy moons will continue: Europa Clipper, Europa lander concept, and JUICE mission. If there are extant or extinct life in Mars, we will probably know it within the next 20 years. Detection of signs of life in icy moons will be more difficult, and will probably require access to potential subsurface oceans. However, if there is exchange of material between the ocean and the surface (such as plumes), detection could also be possible in the orbit or on the surface.

The most of these forthcoming missions and instruments are national or agency based and include overlapping research goals and instruments. However, doing more international collaboration could intensify the efforts of detection habitable environments and biosignatures. Fortunately, the results from different missions and instruments are available to astrobiology community. Creation of an international umbrella organization to astrobiology has proven unsuccessful so far, but the NASA Astrobiology Institute has an important role to promote international astrobiology research. Connecting different institutions and individual researchers, and fostering public knowledge could boost the search for signs of life in the universe.

Seeking non-aqueous life on a hydrocarbon world

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Seeking non-aqueous life on a hydrocarbon world

Introduction

The current paradigm of life requires energy, water, and organic molecules [Hand et al., 2017]. Terrestrial life uses water as an intra- and extracellular solvent to support cellular membranes, transport nutrients, and diffuse reaction products away from catalytic centers. The polar properties of water allow control of the folding and activity of proteins and other biological structures through placement of exposed hydrophilic functional groups. Water is so central to our ideas of life that our highest priority astrobiology targets include worlds possessing significant subsurface oceans such as Europa, Enceladus, and Titan [Hendrix et al., 2017]. But could exotic life use solvents other than water? Could the hydrocarbon lakes of Saturn's moon Titan host non-aqueous biochemistries? What types of signatures would provide evidence of non-aqueous life or non-aqueous prebiotic chemistries?

Cryogenic hydrocarbons as a potential life-supporting solvent

Challenges

Cryogenic methane is a poor solvent, even for organic molecules [Cornet et al., 2015]. This property may limit methane's ability to support a rich and varied biochemistry. Theoretical work and laboratory investigations demonstrate that while small hydrocarbon compounds (e.g. ethylene, acetylene) can have high solubilities in methane under Titan conditions, larger nonpolar or functionalized organics will have "geologically low" (<0.03 mg L^{-1}) solubilities [Malaska et al., 2011]. The situation improves with solvents such as ethane and propane, with up to 100x increases in solubility when compared to methane [Raulin, 1987; Cornet et al., 2015].

Low solubility will decrease the availability and types of molecules that can be used as nutrient or reactant molecules. In methane-based liquids, only small non-polar molecules will be soluble and thus available as building blocks to construct larger structures. At catalytic centers, the joining of two small soluble molecules will result in a larger insoluble molecule that will block access to the catalytic center, resulting in decreased, if not zero, catalytic turnover. Energy carriers used to shuttle chemical energy around the cell (terrestrial systems use dissolved ATP and NADPH) will also need to be soluble in methane for transport. Thus, in a purely methane solution, potential energy carriers are limited to small and unfunctionalized hydrocarbons. (Amino acids and peptides, the building blocks of terrestrial catalytic enzymes, are insoluble in liquid methane.)

Opportunities

Although these solubility challenges require different types of building blocks and molecular constructs than on Earth, the low solubility also presents opportunities as molecules may self-organize through comparatively weaker intermolecular interactions. Weak molecular interactions will be favored in Titan's cryogenic environment (94 K at the surface) that decreases the relative kinetic energy of the molecules and allows a wide range of weak non-covalent interactions to play a role. As an example, theoretical calculations have suggested that the simple molecule acrylonitrile (CH_2CHCN) may aggregate in liquid methane to form a new type of membrane-like structure, an azotosome, due to the relatively strong intermolecular bonds between acrylonitrile with itself compared to a methane-acrylonitrile solvent-solute interaction [Stevenson et al., 2015]. Recently, other theoretical calculations investigated the feasibility of a non-hydrolyzable CHN biochemistry for hydrocarbon solvents [Lv et al., 2017].

The typical reversible reactions used by aqueous life, amide-bond formation and metabolic hydrolysis, have high activation energies that are not easily accessible at cryogenic temperatures. Instead, weaker non-covalent interactions (pi-pi, sulfur-lone pair→pi, halogen bonds, hydrogen bonds, London dispersion forces, permanent dipole→transient dipole, etc.) could allow constructs not possible at terrestrial temperatures to exist. This is also illustrated by an ethane-benzene co-crystal molecular structure that exists under Titan conditions but is unstable at elevated temperatures [Cable et al., 2014; Maynard-Casely et al., 2016].

The challenges associated with low solubilyt may also be mitigated by the presence of alternative solvents. Solvents such as ethane and propane are surprisingly absent from the larger surface seas of Titan but may comprise up to 38% of the southern Ontario Lacus [Mastrogiuseppe et al., 2018]. Both species are produced in significant amounts by Titan photochemistry and may have existed more abundantly in the seas at some epochs before retreating into the crust. These longer hydrocarbon chain solvents will result in increased solubility for organics, but still allow low-energy interactions to occur. Laboratory and theoretical work has only begun to investigate cryogenic reactions and structures that could exist on the surface and shallow subsurface of Titan's liquid hydrocarbon reservoirs.

While cryogenic temperatures can hinder chemical reactivity due to decreased reaction rates of most chemical reactions, recent work has revealed the potential for covalent chemistry to occur even at Titan surface conditions. Gudapati et al [2015] demonstrated that near-surface photo-chemistry could occur from long-wavelength light that penetrates Titan's haze. Other examples include the formation of benzene from acetylene through cosmic ray interaction [Zhou et al., 2010] and the reaction of amines with carbon dioxide to form carbamic acids at temperatures as low as 40 K [Hodyss et al., 2016]. With each new reaction unveiled, the number of possible reactions that could make up a cryogenic non-aqueous biochemical manifold increases.

Titan presents diverse environments for non-aqueous life

A National Academies 2007 study determined that "the environment of Titan meets the absolute requirements for life" based on two key factors: 1) Titan possess a rich diversity of organic molecules and 2) a fluid environment [National Research Council, 2007, p. 74]. Since the 2007 study, thanks to Cassini-Huygens observations, laboratory experiments, and theoretical investigations, we now know that Titan's surface is covered by a thick mantle of vast organic plains, equatorial organic dunes, and thick plateaus composed of organic materials [Lorenz et al. 2008; Malaska et al., 2016]. A combination of remote sensing and laboratory experimentation provided bathymetry and compositional constraints of Titan's lakes. These measurements have shown the northernmost lakes and seas to be methane/nitrogen-rich and the largest lake in the southern hemisphere, Ontario Lacus, to be primarily composed of methane, ethane, and dissolved nitrogen. As the *Cassini* mission progressed, our view of Titan has changed from an icy world with ethane lakes and dunes to an organic world with vast organic deposits and methane-rich lakes with a possible hidden reservoir of ethane present in the subsurface.

From our evolving understanding of Titan's surface, the data lead us to suggest that non-aqueous life could exist in several environments on Titan:

- *Lakes:* Titan's cryogenic hydrocarbon lakes cover 3% of the surface. Large seas and small lakes in the northern hemisphere appear divided into separate drainage basins. In the south, Ontario Lacus may contain more organic materials due to concentration by evaporation, as well as a larger amount of ethane than the northern lakes [Cornet et al. 2012; Mastroguiseppe et al., 2018]. The lakes may be locations where rivers and channels could deliver chemical precursors derived from atmospheric photochemistry and may thus be relatively rich in chemical resources.
- *Lakeshores*: Titan's lakeshores provide locations where evaporite deposits [MacKenzie et al., 2014; Cordier et al., 2016] and other sediments can sequester increased concentrations of organic molecules [Malaska et al., 2012].
- *Porous regolith, or deep subsurface hydrocarbon reservoirs [Hayes et al., 2010; Mousis et al., 2016]*: These may have a different liquid compositions due to evaporation and layering of volatile methane on top of more refractory (and slightly denser) ethane or even higher hydrocarbons [Stephenson and Potter, 1986]. Deep springs in Titan lakes could also deliver materials and chemicals from subsurface aquifers into the bottom of Titan lakes. Other locations could include very deep organic reservoirs in the crust at varying temperatures and pressures, perhaps with supercritical fluids, that could include appreciable amounts of dissolved water or other co-solvents [Lorenz et al., 2008]. Relatively little work has been done on possible biochemistries that could exist under these conditions.

Recognizing non-aqueous life

As with other life detection strategies, the key will be to look for a deviation from the expected abiotic background [McKay, 2016]. These deviations could manifest via morphological, chemical, isotopic, and/or chiral signatures.

- *Morphology*: Recognizing biological structures in non-aqueous environments will require a better understanding of the various minerals that could occur abiotically on Titan (such as co-crystals) [Maynard-Casely et al., in press] and further theoretical refinement of predictions for cell-like structures such as those proposed by Stevenson et al. [2015] or large sheets formed of HCN polymers [Rahm et al 2017].
- *Chemical distribution*: The distribution of chemical products in an abiotic system will follow predictable rules of product distribution based on chemical activation barriers. Any aberrations from this distribution could be the result of a biological system [McKay and Smith, 2005; Strobel, 2010; McKay, 2014]. A terrestrial example is the distribution of saturated linear carboxylic acids, and amino acids [Dorn et al., 2011]. Linear unsaturated carboxylic acids found in living systems exhibit an even/odd abundance pattern. The amino acid distribution pattern resulting from biological systems gives approximately equal abundance regardless of side chain complexity for the 20 biotic amino acids. Similar patterns indicative of biology could be seen in non-aqueous cryogenic hydrocarbon solvents [Lv et al., 2017].
- *Chirality*: Given an abiotic achiral synthesis and degradation environment, there should be no enantiomeric excess. Any evidence of a preferred enantiomeric excess could result

from chiral templating from a biotic or prebiotic catalyst, providing evidence that some form of competitive optimization or evolution has taken place. Other chiral constructs may also be possible, such as chiral supramolecular constructs created from intermolecular asymmetric grouping of several molecules (e.g. spiral arrangements). These may not be preserved at higher temperatures where the constructs dissociate and reform, however.

- *Isotopic fractionation:* The isotopic distribution in a molecule is an indicator of its synthesis and degradation pathways [Kuga et al., 2014]. An unexpected isotope ratio found in a Titan lake, or even in the lower atmosphere, would suggest an undiscovered chemical pathway, possibly biological, may exist. However, natural partitioning effects, from various surface and subsurface reservoirs in limited communication would have to be understood and accounted for to exclude geological and bulk physical mechanisms [Mousis et al., 2016].

Identification of these signatures will require a deep understanding of the abiotic chemical synthesis and degradative processes that occur in Titan's atmosphere, surface, and liquids.

Conclusions

The cryogenic hydrocarbon environments on Titan present unique opportunities for exploring the potential for organic molecules to organize into non-aqueous chemical systems and supramolecular structures that could develop into a non-aqueous biochemistry. Many of the strategies employed for examining life in aqueous environments can also be adapted to looking for biotic processes in cryogenic hydrocarbon solvents. The locations corresponding to aqueous life sampling locations--surface liquids, deep subsurface hydrocarbon liquid reservoirs--are also viable targets for corresponding non-aqueous environments on Titan. Much of the cryogenic organic chemistry, organic mineralogy, and potential for catalytic and surface chemistry at Titan conditions still remains unknown and needs to be thoroughly investigated using both theoretical and laboratory research. Combined, these investigations will serve as the backdrop for *in situ* sampling for exotic life on Titan and other hydrocarbon worlds.

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Just Look!

A white paper for input to the NAS astrobiology science strategy panel

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Introduction

No NASA mission since Viking 1-2 in 1976 has attempted to find extant extraterrestrial life [1]. Four NASA missions have landed successfully on Mars since the Viking 1-2 (Pathfinder, Mars Exploration Rovers, Phoenix and Mars Science Laboratory). Until 2008 it had not been suspected that liquid saline water could exist near the surface of Mars at current climate conditions, so missions have been explicitly designed to seek signs of past "habitability"— not life *per se*. This has been done in the past mostly by inferring the past or present existence of liquid water using mineral indicators. The next step, however, is to search for biomarkers and also to understand what other parameter(s) habitability involves, an issue recognized by NASA's latest Astrobiology Strategy [2]. Microscopic methods are of high importance for this type of investigation.

Since publication of the Astrobiology Strategy, NASA has been forced to re-examine its approach to life detection when Congressman Culberson wrote a Europa life-detection mission into the congressional budget. The astrobiology community is now tasked with looking for actual life (extinct, extant or both) which is beyond looking for habitability. In the outer Solar System, this almost certainly means looking for remnants of microorganisms or microorganisms themselves.

Searching for Microorganisms

On Earth, remote microbiology has been revolutionized by DNA sequencing. Since we do not know whether extraterrestrial life encodes using DNA (nor should we assume that it does), sequencing is not a good strategy to search for life. Even if extraterrestrial life were based upon DNA, its code would have to be identical to Earth's for sequencing to be meaningful. Other techniques that have been suggested for life detection include the search for target organic molecules by mass spectrometry; spectral fingerprinting using Raman spectroscopy; evaluation of chirality of organic molecules; specific antibody arrays targeting key molecules; and culture-based methods [3-5]. However, by themselves, most of these chemical biosignatures may not be definitive. Many organic building blocks of life are known to also be generated abiotically and have been detected in interstellar space and/or in meteorites with no hint of biotic origin [6]. Homochirality as well may be of abiotic origin [7].

Most importantly, if even the most robust chemical biosignatures are found in the absence of confirmed life, we cannot be sure whether they are precursors to nascent life or molecular remnants of extinct life (or even both). If the goal is to look for extant life, then making this distinction is vital. The way life *looks, behaves, moves,* and *interacts with its environment* is the only way that we have of clearly distinguishing it from complex abiotic chemical reactions [8]. Indeed, currently science does not have a reductionist definition of life [9].

The challenge of detecting microbial life on any extraterrestrial planetary body is tremendous. Europa's ice shell is at least several kilometers thick. Ionizing radiation from Jupiter's magnetosphere, primarily high energy electrons and secondary bremsstrahlung, creates a surface dose level of 3000 Gray/month (falling to ~1 Gray/month one meter below the surface) [10]. Several attempts have been made to estimate the available carbon and carbon flux rates in the Europan subsurface ocean, with a conclusion that the entire ocean may support as few as 10^{21} bacterial cells [11]. If they were homogeneously distributed, this would be < 1 cell/L (although it is important to note that homogeneous distribution is highly unlikely). To prepare for this challenge we need develop methods that can detect microbial life from any Earth environment, without underlying assumptions about chemical composition that may not be generalizable to life elsewhere. This will only be possible with a suite of measurements in which direct imaging plays a key role.

Gold Standards on Earth

For identification and enumeration of microscopic life, fluorescent labeling with dyes followed by high-resolution light microscopic imaging is the tool of choice [12]. The most commonly used dyes produce low background fluorescence, with a strong quantum yield increase upon binding to chemical targets (DAPI and acridine orange are examples). Fluorescence imaging increases the specific signal relative to the background, facilitating observation and counting. It also increases effective spatial resolution by allowing cellular features that are unresolved, such as flagella, to be seen.

Despite its ubiquity on Earth, *high-resolution light microscopy has been notably absent* in *in situ* planetary instruments. This is due in part to technical challenges: most microscopy techniques require expert manipulation and are sensitive to vibration and temperature extremes, and high resolution microscopes are often large, heavy, and fragile. However, recent advances have allowed for sub-micrometer resolution in compact, robust, autonomous instruments.

Requirements for Imaging Microscopic Life

Micron-scale cells often have few physical features that distinguish them from debris. Even the use of dyes can be ambiguous, as dyes can bind to mineral particles. Simply increasing spatial resolution is not the answer; electron microscopy can be inconclusive in distinguishing microbes from minerals, as exemplified by the ALH84001 meteorite controversy [13]. Definitive detection of microbial life requires several elements: context, chemical composition, and ideally activity consistent with life (growth, motility, or cell division). When organisms are non-motile, the existence of multiple cell-like objects with some hint of organic chemical composition is required to imply that life is present. Fluorescence microscopy can give that hint to composition. Dyes can target nucleic acids (including nucleic acids not used in Earth life such as PNA [peptide nucleic acid] [14]); lipids, which are considered a likely universal biosignature [15]; and various other cell wall and membrane components. While these do imply some pre-supposition of extraterrestrial chemistry, the classes of molecules stained are broad enough that they are likely to exist on all water-based worlds containing life.

Microscopes for Planetary Missions

The report of the Europa Lander Science Definition Team (SDT) released in 2017 specifically identified an investment in the development of advanced microscope technologies as a key finding and included a microscope as a baseline instrument for the first Europa lander, identifying desired performance parameters as: *"Search for cells and other microstructures that are 0.2 micron or larger in their longest dimension; Measure structural, compositional, and/or functional properties such as biophysical or mechanical properties, native autofluorescence, or microspectroscopic signatures, associated with microscale particles in the sampled material."* [16]

Fluorescence microscopy is ubiquitous in biology, and is universally used in studies of extraterrestrial analog samples such as sea ice, desert soils, and endolithic communities. Autofluorescence is usually too weak to be of value unless the organisms contain chlorophyll, which means dyes must be used; each environment requires special handling and staining considerations, and an informed choice of dyes. Studies in Earth extreme environments are of immense value in designing an extraterrestrial mission, as they will inform hardware and protocol design: choice of excitation/emission wavelengths, need for sample filtration/washing, and choice of imaging temperature.

Fluorescence Microscopy

A fluorescence microscope has not yet been used on another planet, but some are in the pipeline. JAXA had been studying a mission concept for 2020 or 2022 launch called MELOS

(Mars Exploration of Life-Organism Search). The mission included a rover carrying a fluorescence microscope, i.e., the LDM (Life Detection Microscope) [17]. Though the mission was not accepted for the launch window, the LDM team is continuing the development of the instrument. The goal will be to use the dyes SYTO24 and propidium iodide together, a green/red live/dead combination. Both dyes are essentially non-fluorescent until they bind nucleic acids, so they may be used in soil and rock samples with no wash steps needed (**Fig. 1**), although both can show false positives on minerals. Not all details of the microscope design or dyes are available yet, but the target mass is 6 kg, power 20 W, and spatial resolution 1 μm. The limit of detection is ~10^4 cells/g of clay soil.

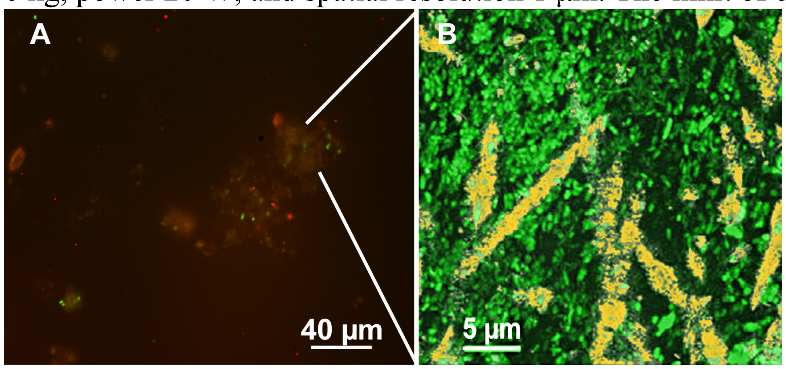

Figure 1. Live/Dead stain in environmental samples with no wash steps. (A) Low power image of Arctic biofilm sample showing individual live (green) and dead (red) cells with little mineral labeling. (B) Confocal section through an area of the biofilm showing a tremendous density of live cells (green). The yellow is mineral reflectance imaged by collecting a fraction of the excitation light.

The *Biological Oxidant and Life Detection (BOLD)* mission was a mission concept proposed in 2012 [18]. The general design involved 6 small probes capable of partial impact for subsurface access, each containing a life-detection or habitability-characterizing instrument. One of the proposed instruments was a microscope with the following characteristics: capable of both context imaging (~20 μm resolution) and high-resolution imaging (~1 μm); LED illumination with UV and red, green, and blue light; laser fluorescence excitation with labeling with 3 dyes (dyes not specified, but UV excitation is suggested) [18]. It is important to note that the microscope described is a concept only. Members of the BOLD team have constructed a multiscale imager for astrobiology that incorporates many of the desired features, particularly the ability to image in context and then zoom in to 1.2 μm resolution [19]. The instruments discussed are based upon traditional optics, with objective lenses and probably moving parts such as turrets and focus mechanisms; mass is on the order of 1-2 kg. However, significant miniaturization is possible based upon modern micro-electromechanical systems (MEMS) technology. Fluorescence microscopes have been made extremely small for biomedicine; the entire package, not including computer, can be < 2.5 cm^3 and < 2 g [20]. Confocal sectioning is possible through a variety of designs: one example is through the use of an electrowetting lens with variable focus [21].

Digital Holographic Microscopy (DHM)

Holography is an interferometric technique that encodes the electric field of a 3D object as a pattern of fringes caused by the interference of a clean reference beam with a beam that has passed through the object. A hologram is not an image in the traditional sense; its intensity is given by a pattern of interference fringes which can be reconstructed into intensity (bright-field) and quantitative phase images [22] [23]. The use of holography has the immediate advantages of image compression and lack of need for focusing, both of which are important for space flight. Using phase imaging allows for estimates of particle index of refraction [24] and detection of transparent objects in the absence of stains. To maximize depth of field, DHM is usually performed with coherent light (lasers). A robust off-axis DHM has been reported for imaging of microbes in field applications; spatial resolution is <0.8 μm in a sample volume of 0.4 x 0.4 x 1 mm^3, with 15 fps acquisition rate at 2048 x 2048. Prokaryotic cells and their activity are readily visualized with this instrument with a limit of detection of ~10^4 organisms mL^{-1} (**Fig. 2**).

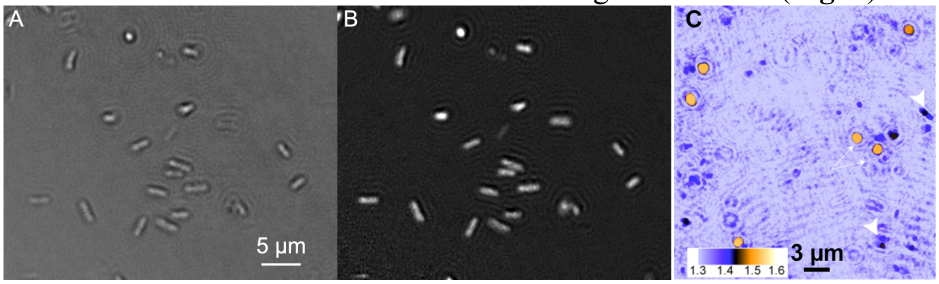

Figure 2. DHM images of *E. coli* cells in (A) amplitude and (B) phase. (C) Distinguishing *E. coli* phase images from 1.5 µm alumina beads. The color bar indicates estimated refractive index. The beads (yellow) are readily distinguished from the cells (blue, arrowheads) since living cells have refractive indices close to that of water (~1.35).

Digital in-line holographic microscopy (DIHM) may be performed on diluted samples with only a single beam that serves as its own reference, with the deviation caused by the sample considered as a perturbation. DIHM imposes additional complications on the reconstruction, but rapid algorithms have been developed for this [25]. At least two commercial DIHMs have been developed for submersible use and are used to image plankton and particulate matter. One is commercially available from 4-Deep [26,27] and another from Sequoia Scientific [28,29]. Spatial resolution of these in-line instruments is insufficient for microscopic life (10-20 µm); on the other hand, their sample volumes are very large (50 mm deep). DIHMs using incoherent light may be made extremely compact. Mainly developed for medical applications, they can show a field of view of 24 mm^2 without scanning, in an instrument < 100 g [30].

Atomic Force Microscopy (AFM)

Two atomic force microscopes (AFMs) have flown on planetary missions. First was the Micro-Imaging Dust Analysis System (MIDAS) AFM on the Rosetta mission, targeting Jupiter family comet 67P Churyumov-Gerasimenko. MIDAS's goal was to study the size, shape, and morphology of cometary dust particles with a spatial resolution of 4 nm [31]. MECA (the Microscopy, Electrochemistry, and Conductivity Analyzer) on the Phoenix Mars lander (2007) had an AFM to determine particle size distribution (PSD) of fines in the Martian regolith. It was coupled with an optical microscope with 4 µm/pixel that permitted pre-selection of areas to image [32], an advantage that MIDAS did not have [33]. AFM images of biological cells can be spectacular, showing nm scale features such as flagella in great detail; physical properties can also be inferred [34]. The problem is throughput; AFM alone would be insufficient for scanning large sample volumes.

Conclusion

Life detection will remain ambiguous until something alive is imaged. Although the current technology for imaging microscopic microbial life is fairly mature for terrestrial applications, it needs further refinement for *in situ* space applications. Future work in Earth analog sites is essential to develop protocols for labeling, sample concentration, and imaging that are appropriate for future mission targets.

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From Nucleotides to a LUCA

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Abstract

Around 4.1 billion years ago, the building blocks of life were carried to Earth on meteorites. Aboard these meteorites were important organic compounds that play a significant role in the creation of life.[1] These chemicals, coupled with early Earth's environment allowed non-living chemical compounds to evolve into the very first life forms. Over the course of millions of years, nucleic acids formed and began to evolve into what we know as the last universal common ancestor. By investigating how a LUCA came to be, we can better understand life on Earth as well as how life might form on other planets.

Introduction

Scientists can hardly find a bigger question. How did life begin? This short and simple question has been asked for centuries. Unfortunately, a clear answer has yet to be acknowledged. Handfuls of theories suggest that life first formed with RNA. Others say it all started with proteins. Millions of years later a last universal common ancestor, or LUCA, came to be. Supposedly, all life forms share common traits that originated in this first organism. This theory does support what may have happened millions of years ago, but not fully. We still don't know how a LUCA started. This area of research has gained popularity, and scientists are working harder than ever to discover the origins of life.

First nucleic acids on Earth

During the Hadean Eon, carbonaceous meteorites pelted Earth,[2] delivering chemical compounds that make up RNA and DNA. A team headed by Michael P. Callahan analyzed 12 different carbonaceous meteorites and found that 11 had at least one nucleobase.[3] If the meteorites that struck early Earth had the same composition as the ones Callahan's team analyzed, they would have been able to polymerize into nucleic acids. Whether RNA, DNA, or proteins came first has been heavily debated for years but new research points towards the former being true.

Thousands of ponds scattering the Earth's surface were easy targets for meteorites to land in, depositing nucleobases key to RNA creation.[1] Additionally, the wet and dry cycles of these ponds accelerated the polymerization of the nucleobases into nucleotides.[1] Although this hypothesis has been around since Darwin, scientists at McMaster University and the Max Planck Institute have reinforced it by running numerous calculations.[1] This theory is new and has its caveats, for one, the pond seepage and UV photodissociation causes formed nucleotides to be lost. They would have to form at a steady rate in order to evolve into a sustainable life form.

Another group of scientists from The Scripps Research Institute have succeeded in creating a polymerase ribozyme capable of replicating RNA from templates without the help of proteins.[4] This proves that primitive organisms could survive solely on RNA.

Evolution of RNA/DNA into a LUCA

Being a complex molecule, RNA can both retain genetic information and catalyze its replication.[5, 6] With this knowledge, many scientists believe that RNA molecules were the ones to develop into organisms, such as a LUCA. Natural selection plays a big role in this evolution process. Once the first self-replicating molecules formed, variants emerged from mutations. Better versions, or faster producers formed over time. Along with improvement, these molecules became more common. Through this process, more drastic changes began to emerge. For example, molecules began to create cell membranes. This new addition brought amazing advantages to early life. Obviously, the membrane protects the genetic material from the external environment. With such a drastic change, these new molecules easily out-competed the old ones. This breakthrough helped transform RNA into more complex organisms such as bacteria.

Even though RNA played a significant role in creating complex organisms, DNA soon took tasks that RNA could do, like storing genetic information, and performed better. As molecules advanced and evolved, DNA and proteins specialized in tasks RNA does.[7] With the help of natural selection, this innovation was more efficient and stable, although now, RNA acts as a messenger between DNA and ribosomes to create proteins. At this point simple organisms started evolving into a creature related to all living things on present-day Earth. Even though the fact that simple molecules evolving into the animals of today took millions of years, the process was revolutionary. Scientists to today are humbled by it, but they don't hesitate to ask more complex questions.

Conclusion

Life began forming about 4 billion years ago. This long and complex process wasn't easy, but evolved into the organisms we have today. Scientists and people in modern times can't help but wonder how the origins of life unfolded. It started when meteoroids struck, depositing the ingredients of life into Earth's ecosystems, some of which, had the perfect conditions for polymerizing RNA. This molecule(RNA) was a major building block for complex life. With its ability to self-replicate, this allowed natural selection to come into place. This long process slowly changed basic molecules into more complex bacteria. A simple sounding process is much more complicated when considering it, but provides even more question and topics for us to discover.

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Addressing the Habitability of Europa with the Europa Clipper Mission

A White Paper Submitted to
The National Academies Astrobiology Science Strategy for the Search for Life in the Universe

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Summary: The science goal of the Europa Clipper mission is: *Explore Europa to investigate its habitability*; the mission's three objectives are focused on Europa's ice shell and ocean, composition, and geology. The science goal and objectives will be addressed with a capable and synergistic suite of remote sensing and *in situ* instruments.

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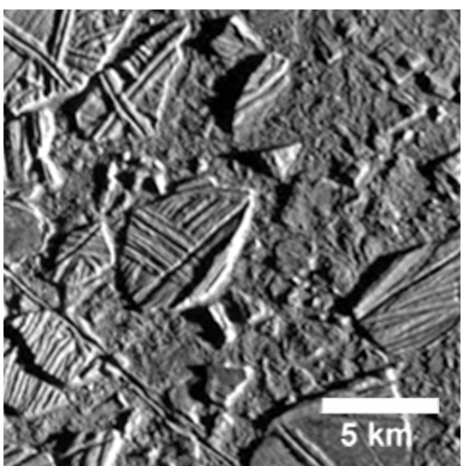
The ice-covered world Europa—one of the four large Galilean satellites—may be the best place in the solar system to look for extant life beyond Earth. Europa is about the same size as Earth's Moon and is mostly rock, with an outer ice-rich shell that is quite dynamic. Its young, bright, icy landscape is crisscrossed by a network of cracks and ridges, interrupted by smooth bands, disrupted chaotic terrain, and few large craters [see *Greeley et al.*, 2004, and references therein].

Several lines of scientific evidence point to the conclusions that Europa likely has a global ocean of liquid water under the ice, maintained by tidal flexing and consequent heating as the moon moves in its eccentric orbit about Jupiter [see *McKinnon et al.*, 2009, and references therein]. The orbital eccentricity is maintained by resonances with the other Galilean moons and is likely long-lived. While the presence of the ocean is almost inarguable, whether Europa is habitable is unknown [see *Hand et al.*, 2009, and references within].

For these reasons, future investigation of Europa is a top priority for planetary exploration, as expressed in the National Research Council's planetary science decadal surveys [*NRC*, 2003, 2011]. NASA's Europa Clipper mission, currently in Phase B, will enable a leap in scientific understanding of ocean worlds and their potential habitability.

Previous Explorations

Observations of Europa by the twin Voyager spacecraft in the late 1970s first revealed Europa's enigmatic linear features, but at only relatively low resolution, providing more questions than answers. The Galileo spacecraft, which orbited Jupiter from 1995 to 2003, obtained the first high-resolution images and spectra of a variety of Europa's surface terrain types, along with the first close-up fields and particles observations.



Images revealed iceberg-like, chaotic terrains, which seem to consist of icy crustal blocks that have been broken apart, rotated, translated, and tilted before being refrozen into new positions. Bull's-eye-like impact structures suggested that forming craters were able to penetrate to an ocean about 20 kilometers below the surface. Surface geology lent credence to the idea that the floating icy shell could undergo solid-state convection today, driven by tidal flexing and heating. Spectra suggest that salts exposed on the surface potentially reflect the chemical signature of a salty ocean, along with radiolytic products.

Observations by Galileo's magnetometer of local non-dipolar magnetic fields suggest that Europa's motion through the Jovian field induces eddy currents in a salty subsurface ocean which in turn induce a local magnetic field [*Zimmer et al.,* 2000]. Charged particle irradiation of the surface creates oxidants, which, if transported to the subsurface ocean, could potentially serve as a fuel for simple forms of life.

Mysterious Ocean World

Even with these preliminary data sets, Europa's youthful surface, subsurface ocean, and ongoing tidal flexing suggest that it may be geologically active today. However, the data return from the Galileo mission was limited, and the mission was not designed to make the key measurements needed to determine the depth to the ocean, presence of organics, and whether the ocean is expressed on the surface [see *Prockter and Pappalardo,* 2014, and references therein].

For example, Galileo's Doppler gravity measurements [*Anderson et al.*, 1997] imply the ice and liquid H_2O layer totals 80–150 kilometers thick, but we do not have a certain measurement of the thickness of the ice shell itself. There is no definitive evidence of surface changes attributable to geological activity [*Phillips et al.,* 2000]. However, recent observations using ultraviolet images from the Hubble Space Telescope [*Roth et al.,* 2014; *Sparks et al.,* 2017] suggest that vapor plumes may currently be venting water from Europa's subsurface.

Models for the formation of Europa's unusual surface features have matured but remain inconclusive. Spectroscopy indicates surface hydrated salts and radiolytic compounds, but identification of specific species has not been possible. Organics have not been identified, but may be beyond the capacity of the Galileo near-infrared spectrometer. Fundamentally, it is not yet known if Europa has sufficient energy sources to sustain a biosphere. The frontier is to determine whether the interior ocean of Europa represents a habitable environment.

The Europa Clipper Mission

The Europa Clipper mission [*Pappalardo and Goldstein,* 2013] is currently in development by NASA for launch in the 2020s. The mission will provide the critical data required to answer the highest-priority geophysical and astrobiological questions about this intriguing ocean world. The Europa Clipper mission will address its science goal by flying past the moon repeatedly and observing with a payload specifically designed to address potential habitability. "Habitability" as defined in the solar system exploration context refers to the ability for a planetary environment to support microorganisms analogous to known terrestrial ones in the sense of being carbon-based and requiring an abiotic environment [e.g., *Chyba and Phillips,* 2001; cf. *NRC*, 2007].

From its elliptical orbit of Jupiter, the Europa Clipper will conduct more than 40 close flybys of Europa over about 3.5 years. Most of the flybys will have a closest approach in the range of 25–100 km, typically with a 14-day flyby cadence. By orbiting Jupiter rather than Europa directly, the solar-powered Europa Clipper spacecraft will spend most of its time outside of the high-radiation environment close to Jupiter that can be damaging to the spacecraft and payload. On each orbital pass, the remote sensing instruments will be employed to study Europa's surface and subsurface, while its *in situ* instruments will detect plasma, neutral, and dust particles from Europa's tenuous atmosphere, external environment, and magnetic field. The spacecraft's radio signal will be tracked from Earth to measure Europa's gravitational field. When farther from Europa, the spacecraft will transmit its bounty of data back to Earth.

A key feature of the mission design is that the Europa Clipper will use gravitational perturbations from Ganymede, Callisto, and Europa itself to deflect its trajectory, allowing the spacecraft to return to a different close approach point with each flyby. The flyby paths will create an intersecting web, allowing globally distributed remote and *in situ* interrogation of different regions of the surface, atmosphere, and space environment over time.

Europa Clipper Science Goal, Objectives, and Investigations

The science goal for the mission is to *explore Europa to investigate its habitability.* Table 1 articulates the three Science Objectives to attain this goal, which involve investigating Europa's ice shell and ocean, composition, and geology, as well as the ten Mission Investigations that flow from them. Folded into the three Science Objectives is the desire to search for and characterize any current activity, notably plumes and thermal anomalies. Table 1 also notes the key instruments (see Table 2) which synergistically address each Mission Investigation.

Table 1. Europa Clipper Goal, Objectives, Investigations, and Instrument Synergies

Goal	Science Objective	Mission Investigation	Key Synergies
Explore Europa to investigate its habitability	**Ice Shell & Ocean:** Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange.	Characterize the distribution of any shallow subsurface water and the structure of the icy shell.	EIS, REASON
		Determine ocean salinity and thickness.	ICEMAG, MISE, PIMS, SUDA
		Constrain the regional and global thickness, heat-flow, and dynamics of the ice shell.	E-THEMIS, EIS, Gravity, ICEMAG, PIMS, REASON
		Investigate processes governing material exchange among the ocean, ice shell, surface, and atmosphere.	EIS, ICEMAG, MASPEX, MISE, REASON, SUDA
	Composition: Understand the habitability of Europa's ocean through composition and chemistry.	Characterize the composition and chemistry of endogenic materials on the surface and in the atmosphere, including potential plumes.	EIS, Europa-UVS, ICEMAG, MASPEX, MISE, PIMS, REASON, SUDA
		Determine the role of the radiation and plasma environment in creating and processing the atmosphere and surface materials.	EIS, Europa-UVS, MASPEX, MISE, PIMS, Radiation Monitors, REASON, SUDA
		Characterize the chemical and compositional pathways in the ocean.	EIS, ICEMAG, MASPEX, MISE, SUDA
	Geology: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.	Determine sites of most recent geological activity, including potential plumes, and characterize localities of high science interest and potential future landing sites.	E-THEMIS, EIS, Europa-UVS, MASPEX, MISE, PIMS, Radiation Monitors, REASON, SUDA
		Determine the formation and three-dimensional characteristics of magmatic, tectonic, and impact landforms.	EIS, REASON
		Investigate processes of erosion and deposition and their effects on the physical properties of the surface.	E-THEMIS, EIS, Europa-UVS, PIMS, Radiation Monitors, REASON, SUDA

A suite of nine instruments selected by NASA (Table 2) comprises the mission's payload, providing synergistic and robust means to address the Scientific Objectives required to attain the goal of investigating Europa's potential habitability. In addition, Europa Clipper's telecommunications system will be used to track the Doppler signature of the spacecraft, to constrain the gravitational manifestations of Europa's tides and ocean. Additional scientific data comes from the spacecraft's radiation monitoring system and from some instruments' responses to the radiation environment. The payload *in toto* will enable Europa Clipper to seek evidence of subsurface water, of chemistry compatible with habitability, and of active geological processes.

Table 2. Europa Clipper Science Payload

Science Instrument	**Principal Investigator / Institution**	**Instrument Investigation Summary**
Europa Ultraviolet Spectrograph (Europa-UVS)	Kurt Retherford Southwest Research Institute, San Antonio TX	Detect possible water plumes erupting from Europa's surface and provide data about the composition and dynamics of Europa's rarefied atmosphere.
Europa Imaging System (EIS)	Elizabeth Turtle Johns Hopkins University Applied Physics Laboratory, Laurel MD	Wide and narrow angle cameras to map most of Europa at better than 100 m/pixel resolution, and some areas up to 100 times higher resolution.
Mapping Imaging Spectrometer for Europa (MISE)	Diana Blaney Jet Propulsion Laboratory, Pasadena CA	Probe Europa's composition, identifying and mapping distributions of organics, salts, acid hydrates, ices, and other materials to determine habitability of Europa's ocean.
Europa Thermal Emission Imaging System (E-THEMIS)	Philip Christenson Arizona State University, Tempe	Provide multispectral thermal imaging of Europa to help detect active sites, such as potential vents erupting plumes of water into space.
Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)	Donald Blankenship University of Texas, Austin	Characterize and sound Europa's icy crust from the near-surface to the ocean, revealing hidden structures and potential water within.
Interior Characterization of Europa using Magnetometry (ICEMAG)	Carol Raymond Jet Propulsion Laboratory, Pasadena CA	Measure the magnetic field near Europa and infer the location, thickness and salinity of Europa's subsurface ocean using multi-frequency electromagnetic sounding.
Plasma Instrument for Magnetic Sounding (PIMS)	Joseph Westlake Johns Hopkins University Applied Physics Laboratory, Laurel MD	Determine plasma-driven magnetic field perturbations to enable inference of ice shell and ocean properties, and measure charged particles in Europa's atmosphere and the Jovian plasma.
Mass Spectrometer for Planetary Exploration / Europa (MASPEX)	Jack (Hunter) Waite Southwest Research Institute, San Antonio TX	Determine composition of the surface and subsurface ocean by measuring Europa's tenuous atmosphere and any surface material ejected into space.
Surface Dust Mass Analyzer (SUDA)	Sascha Kempf University of Colorado, Boulder	Measure composition of small, solid particles ejected from Europa, providing the opportunity to directly sample the surface and potential plumes on low-altitude flybys.

Accommodation of the Europa Clipper instruments orients the remote sensing instruments in a nadir-looking orientation during the period around closest approach, while positioning the particle sensors close to the Keplerian ram direction. This permits all of the instruments to collect data simultaneously during the close flybys, promoting collaborative and synergistic science data analyses, appropriate to the Europa Clipper's multifaceted science objectives. The concept of operations on each flyby is repetitive to the extent feasible, so that planning and operations are simple and cost-effective.

In addition to revealing Europa's potential habitability, Europa Clipper observations can provide a foundation for potential future missions. For example, these observations would provide scientific context for detailed surface interrogation by a possible Europa lander, along with information on the engineering safety of potential landing sites.

If Europa Clipper were to find evidence that Europa’s ocean is habitable, or discover other crustal habitable environments, these discoveries would motivate follow-on missions to search for life. If plumes are currently erupting from Europa, lofting interior material high above the surface, Europa Clipper may even sample the ocean’s contents and conceivably obtain constraints on active biological processes. Identification of surface sites containing organics or other ocean materials would help guide future lander missions with life detection instruments. Exploration of Europa by the Europa Clipper will provide a great leap in understanding the potential habitability of the Solar System's ocean worlds [*Lunine*, 2017], which feasibly could be the most common habitats for life.

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The Critical Enabling Role of Integrated Microfluidic Systems in the Search for Life: Key Challenges, Recent Progress, Path Forward

A White Paper in response to the
ASTROBIOLOGY SCIENCE STRATEGY FOR THE SEARCH FOR LIFE IN THE UNIVERSE

8 January 2018

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White Paper Description

A microfluidic sample processor provides the critical "front end" for the suite of wet-chemical analyses needed to establish life's presence or absence on an ocean world: it enables optimal detection limits, the widest range of target analytes, accurate calibration, and robust blanks, all in support of the best chance of unambiguous detection.

Introduction and Background

The search for evidence of life beyond Earth is a high-priority goal of NASA's space exploration program. Priority targets include organic molecules synthesized by living organisms, key chemical and structural attributes of which are strongly indicative of biogenicity, and which are expected to be more definitive than isotopic or morphological indicators of life.[1] A primary goal of future missions is therefore to assess the nature and inventory of organic compounds in the solar system ("follow the carbon"), with Mars, Europa and Enceladus as main destinations.[2]

The challenges of finding molecular biosignatures in planetary samples are illustrated by the chemical and structural complexity of terrestrial carbon compounds, and interference from inorganic material. Natural terrestrial samples contain large, complex molecules comprised of basic building blocks such as fatty acids or amino acids, ~99.5% of the latter in a bound (polymeric) form; the remainder are "free".[3] Such organics—which are likely, as a class, to be found in any life-supportive environment—can be poorly soluble and difficult to analyze, requiring sophisticated laboratory approaches. It is also expected that relevant organic molecules will be low in concentration in planetary samples due to low production, dilution in water/ice, and high rates of destruction (e.g. by radiation). For Enceladus, models based on an active hydrothermal vent system posit concentrations of the most abundant lipid of ~5 – 200 pg/g in plume ice,[4] several orders of magnitude less than, e.g., the concentration of palmitic acid in Earth's oceans.[5] Methods to address such challenges for remote analyses are being developed, but further effort is required.

Water's key role in the form and function of life's organic/ biochemistry means the search for organic biosignatures demands the superior limits of detection and preservation of molecular detail provided by wet chemical analyses. Indeed, NASA's 2015 Technological Roadmap states: "*In the ongoing search for life, wet chemical analysis approaches and sensors need to be developed to allow biological signatures or organic material to be characterized.*"

This approach to the detection of molecular biosignatures requires three distinct functions: (1) sample acquisition; (2) sample processing, including extraction as necessary; (3) sample analysis. Sample acquisition and analysis are the most mature of the three functions, with decades of development, many functional prototypes, an ample publication record, and impressive performance demonstrations in laboratory, field, and mission settings. **Fluidic sample processing for wet chemical analysis, however, remains a major technological gap in life-search missions**.

A potential springboard for the development of such spaceflight instrumentation is the series of technical advancements made over the past decade in (bio/chemical)fluidic sample management and analysis for small satellite missions implementing both space biological and astrobiological investigations.[6-10] That technology is now being adapted, configured, and matured for the requirements of life-search missions. **We recommend that the Astrobiology Strategy acknowledge and emphasize the need for wet chemical analysis in general, and fluidic sample processing in particular, in the search for evidence of life beyond Earth**.

Microfluidic Systems as Critical Enablers for in-situ Life Search: Rationale, Approach, and Technological Progress Since 2015

<u>Measurement Targets: Analytical Approaches drive Sample Processor Functions.</u> A microfluidic sample processor enables and enhances spacecraft-based instrument performance by providing wet-chemical processing of samples obtained above, on, or beneath planetary surfaces. Accordingly, science-driven instrument requirements, including input, blank, and calibration requirements, drive the fluidic processor's capabilities. Table 1 presents a prototypical set of science

measurement targets along with the analytical approaches they need for optimal performance.

Table 1. Measurement Targets, Fluidics-Enabled Approaches, and Measurement Parameters

Measurement Targets*	Example Approaches	Measured Parameters
Organic molecules of potential biological origin	Mass Spectroscopy	Molecular weight distribution & structural characteristics
	Capillary Electrophoresis	Amino acids, including chiral distributions
Microscale indicators of life	Light (visible) Microscopy	Morphological, textural, structural imaging, including cells
	Fluorescence Microscopy	Chemical Structural, compositional, and functional properties
	Deep-UV Microscopy	Native autofluorescence of complex biomolecules
Inorganic indicators of life	Surface-Enhanced Raman	Potential biominerals (e.g., SiO_2, magnetite, iron sulfide)
Chemical factors essential for life and environmental biosignature processing	Electrochemical Sensors	Salts, metals, volatiles (e.g., H_2S, CO_2, SO_2, CO), radiation products (e.g., peroxides, oxyhalides)

*Adapted from Hand *et al.*, Report of the Europa Lander Science Definition Team (2017), JPL D-97667.

<u>Sample Processor: Function drives Form.</u> Finding organic indicators of extraterrestrial life is highly challenging. To do so with optimal use of constrained mass and power requires "preparing" the sample prior to its analysis in order to enable:

(i) wringing maximal performance from each analytical instrument by presenting the sample in a form to enable the best limits of detection (LODs) with the greatest certainty of result;
(ii) optimizing sample collector performance, e.g., consolidating small-volume samples;
(iii) providing standards and calibrants;
(iv) distributing multiple measured aliquots of appropriate volumes to each instrument or sensor for statistically robust measurement outputs;
(v) leveraging sample-preparation commonalities across instruments to minimize technology development cost, mass, volume, and energy consumption.

The effective, robust way to implement such functions is a monolithic microfluidic "sample processor" that receives a sample, executes a sequence of chemical and physical manipulations to prepare it for analysis by a suite of sensors and instruments, then delivers multiple sample aliquots, along with blanks and calibrants. Such a system can leverage the immense body of development in the microfluidics and "lab on a chip" disciplines[11,12] that has found application in everything from industrial process control to point-of-need biomedical assays. Microfluidic systems benefit from recent advances in miniature, micro-, and nano- technologies ranging from polymer (micro)fabrication to inte-

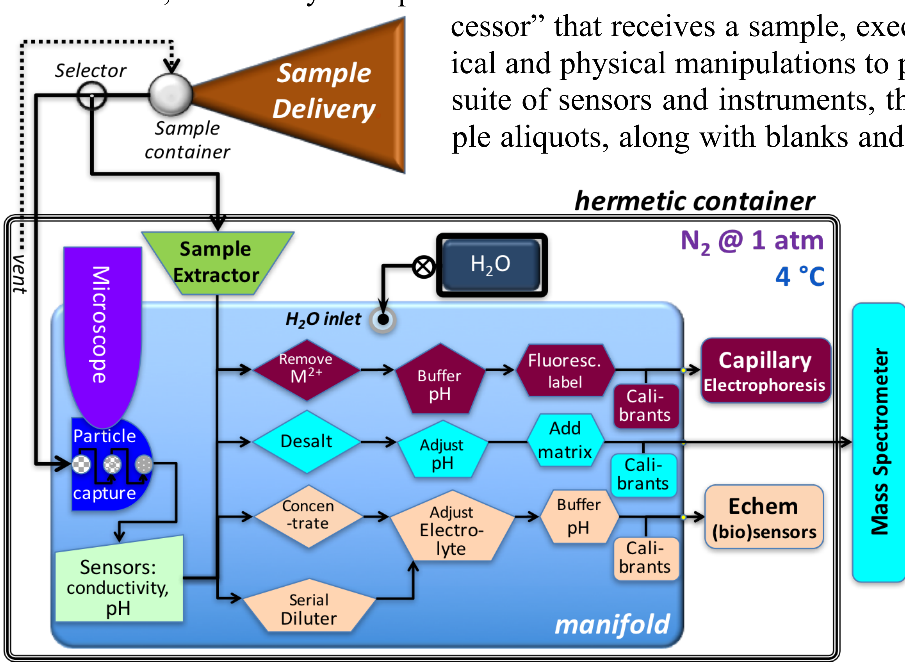

Figure 1. Schematic block diagram of sample processor: configurations & components suitable for Enceladus/Europa samples and, with appropriate sample extraction, martian samples. This system supports a diverse suite of 3 analytical instruments.

grated optics to high-performance sensors and materials for extreme environments. Size, mass, and power consumption generally diminish as performance improves; microfabrication methods provide component parallelism and redundancy at minimal marginal cost.

A functional block diagram of such a system (**Fig 1**) shows a range of functions and the architecture that follows. Further enumerated below, they are geared toward samples potentially obtained at the icy moons Enceladus or Europa, but could be adapted to processed samples on Mars.

Receiving & managing samples. A recently developed mission scenario would assay particles collected from Enceladus' icy plumes. Modeling indicates a collected mass of ~2 mg of ice per orbital pass,[13] or a melted sample volume of 2 µL, for a one-m^2 collector area. The collector would deliver the particles to a sample container, which, after sealing under vacuum and warming to 4 °C, would add sufficient purified water to bring the sample volume to 50 µL (a single drop of water). Measurements in our laboratory using a prototype of this sample chamber show how its thin-layer format (1 mm deep, 8 mm diameter) harnesses capillary forces and surface tension to **transfer >95% of the sample to the processor manifold**[14] (N_2 backfill displaces transferred sample). A selector valve can direct sample to multiple analytical systems after it has been processed in a sequence of steps tailored to each instrument (**Fig 1**).

Only with fluidic "microcircuitry" can a **50 µL sample support separate analytical measurement systems** with a sequence of processing steps culminating in delivery without additional dilution; in fact, we recently demonstrated a vacuum-driven **concentrator that provides > 100-fold sample concentration**, more than compensating the initial 24-fold dilution.[14] Note that the microchannels of our prototype Sample Processor for Life on Icy worlds (SPLIce) manifold (**Fig 2**) contain volumes of just 300 nL/cm of length. Because flow through such channels is entirely laminar, a plug of sample can be "pushed" from behind with pure water (or buffer) with negligible interfacial mixing, permitting the vast majority of the original (processed) sample to be delivered to the measurement instruments.

Exemplary sample processor functions. A typical set of fluidic functions and components accomplished by and integrated into the sample processor are listed here. **Those in bold have already been implemented and successfully tested in our laboratories:**[14]

- **Deliver water to the sample collector to provide adequate sample transport volume**
- **Quantitatively retrieve diluted sample** including suspended particles
- **Separate insoluble sample particles (for microscopy, segregate by size)**
- **Store dry reagents on high-surface-area solid supports for rapid dissolution & reaction**
- **Admix fluorogenic labels, dyes, reagents**
- **Stain particles *in-situ* for microscopy**
- **Degas / remove bubbles**
- Remove specific interfering ions
- Measure / **adjust / buffer pH**
- Adjust solvent polarity / dielectric properties
- Measure / adjust ionic strength / desalt

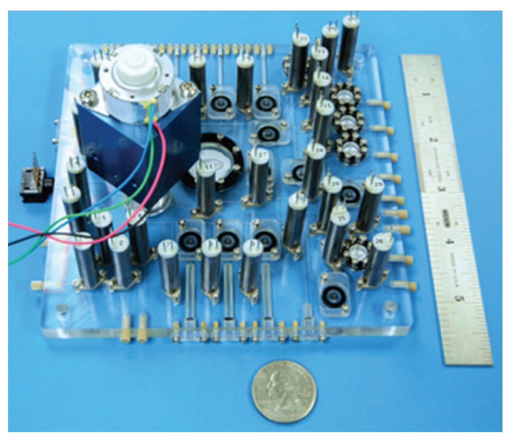

Figure 2*. Photo of prototype SPLIce monolithic manifold, fabricated using multilayer polymer-fusion bonding in combination with ultra-precision machining. Metering pump (blue) is visible at upper left, with two dozen solenoid valves, a concentrator (black ring, partially obscured by pump), 9 check valves, 4 bubble traps, multiple reagent-storage channels, and numerous capillary connectors along the manifold edges. Scale in inches.*

- **Concentrate samples**
- **Dilute samples** (if required for sufficient volume or high-concentration targets)
- Provide calibration standards, positive controls, and negative controls including blanks
- Deliver sample aliquots free of particles > 0.2 μm to multiple analytical instruments

Delivering calibrants, standards, blanks and samples. The sample processor prepares and delivers multiple precisely-measured sample aliquots to each analytical instrument, and it also stores and prepares calibrants and standards; these functions are critical to measurement accuracy and certainty. "Sample blanks" are also critical to confirm the absence of interfering contamination that could cause false positives; the blank follows the entire pathway to be used for the sample. If the blank reveals contamination, background subtraction can salvage a meaningful result.

Key Technological Challenges Remaining to Enable in-situ Life Search

Sample Extraction and Processing. Adequate sample processing can break complex associations of target molecules with other organic or inorganic compounds in the sample, extracting them for subsequent processing and analysis. Key challenges to adapting bench-top methods of extraction, and sample processing in general, for flight include development of: (1) disruptive, but nondestructive, sample-extraction techniques suited to a range of relevant biomolecules (fatty acids, amino acids, hydrocarbons), including exploration of solvent systems not flown historically on spacecraft (non-aqueous solvents, subcritical/supercritical water/CO_2), along with novel means of disruption (e.g. microscale acoustics); (2) filtration and phase separation to remove salts and inorganic particles that interfere with detection; (3) concentration of sample extracts to provide detectable signals (the vacuum-driven concentrator we have demonstrated is an important first step); (4) construction of processor systems from inert, inorganic materials, avoiding organic polymers incompatible with solvents; (5) stringent organic cleanliness protocols; (6) rigorous benchmarking of performance using terrestrial analog samples covering a range in age, mineralogy, carbon compound complexity, and concentration; (7) managing the adsorption of target molecules present at ultralow concentrations onto sample-handling and processing component surfaces, which can severely impair sensitive detection. Solutions to such challenges, while well-developed for biomedical diagnostics,[18,19] need to be evaluated for life-detection scenarios.

Contamination Control. The use of microfluidics in NASA astrobiology missions has been limited,[6] but microfluidic technologies developed for Space Biology experimentation with strict cleanliness and sterility requirements do have significant flight heritage.[6-10] Documented understanding of instrument background, including characterization of organics associated with construction through all project phases, combined with removal of undesired organisms and organics, is required. Procedural definition and demonstration of packaging are also needed to ensure that undesired microorganisms, molecules, and polymers are absent or removed so as not to affect results. Processes developed and demonstrated for elimination of viable biological contamination include ethylene oxide sterilization, cold microfiltration of fluids, and high-temperature vacuum bake for compatible components. Yet, going beyond sterility challenges the production of organically-clean instrumentation. Material selection for low outgassing and elimination of relevant organic contaminants through high-temperature, solvent (including acid) processing, or other methods are required. Many current bioburden and contamination-reduction protocols utilized by industry (e.g., medical devices) are not NASA-approved for Class IV planetary missions. Significant investment at both program and flight-project levels is therefore needed to align NASA-accepted planetary-protection and contamination-control processes and procedures with current state-of-the-art instrument materials, manufacturing, and cleaning approaches.

Conclusions

Existing "gold-standard" laboratory techniques for biomarker analysis can overcome the analytical challenges imposed by complex, low-biomass samples. However, these techniques are laborious, require large volumes of consumables, use large amounts of sample, and rely on mechanical manipulation. They are therefore difficult to implement in a mission scenario, making it crucial to develop microfluidic technology to replicate these analytical procedures autonomously and at a microscale while maintaining fidelity of the original benchtop techniques.

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Planetary Protection: A Cross-Cutting Concern, and a Necessity for Basic and Exploration-Driven Research in Astrobiology

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Summary This white paper notes:
1) Planetary protection is an important, cross-cutting concern of high relevance to astrobiology, and is required to ensure that NASA is prepared to provide for safe solar system exploration;
2) Numerous research and technology development areas relevant to planetary protection have already been identified as important to future robotic and human missions; and
3) For all affected missions, planetary protection considerations need to be integrated throughout mission planning and systems development, requiring proactive coordination and collaboration between the planetary protection community and other experts from the earliest stages of mission development.

Introduction

With the adoption of the Outer Space Treaty (U.N. 1967) biological planetary protection became a required element in space research and exploration. Article IX of that Treaty requires that parties pursuing studies of outer space and other celestial bodies should "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." Furthermore, parties to the treaty "where necessary, shall adopt appropriate measures" for the purpose of avoiding harmful contamination and changes to the Earth's environments. While a number of space agencies (e.g., NASA, ESA, CNES) have established their own specific planetary protection policies to guide efforts in this area when conducting interplanetary missions, there is a long history of coordination and collaboration in this area, and a consensus international standard has been developed through COSPAR, the Committee on Space Research (COSPAR) of the International Council for Science (ICSU). Recently (June 2017), the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) recognized "the long-standing role of COSPAR in maintaining the planetary protection policy as a reference standard for spacefaring nations and in guiding compliance with Article IX of the Outer Space Treaty."

The COSPAR Planetary Protection Policy states the need to control forward contamination (life or organic contamination carried from Earth) that might invalidate current or future scientific exploration of a particular solar system body. Concerns about backward contamination (extraterrestrial life carried back to Earth) focus on the potential for harmful contamination of the Earth's biosphere; for human missions, this concern also includes the possible immediate and long-term effects on the health of astronaut explorers from biologically-active materials encountered during exploration.

After extensive (though imperfect) planetary quarantine efforts for both lunar materials and astronauts during the Apollo program, the focus of planetary exploration and planetary protection shifted to robotic missions. In the intervening years, planetary protection policies and practices have matured considerably, often through integration of advice and recommendations from the scientific community in the form of study reports by the Space Studies Board (e.g., NRC 1992;

1997; 2002a & b; 2006; 2009), and from the broader international community (e.g., Kminek et al. 2007; Amman et al. 2012). Planetary protection is now firmly established as a part of robotic mission planning—and should be incorporated in both human and robotic missions at the earliest stages to ensure proper implementation.

The primary goals of the COSPAR policy do not change when human explorers are involved. In developing preliminary guidelines for human missions to Mars, COSPAR noted that the greater capability of human explorers to contribute to the astrobiological exploration of Mars can be realized only if human-associated contamination is controlled and understood (Kminek & Rummel 2015). To ensure human safety while conducting planetary exploration, consideration of planetary protection is essential. The unavoidable, and mostly beneficial association of humans with a huge diversity of commensal microbes means that tailored, appropriate implementation controls, different from those applied to robotic missions, will have to be developed—particularly for future long-duration missions to Mars. There is a real opportunity to emphasize the important cross cutting, feed-forward considerations that planetary protection concerns will involve, and their possible relationship to the detection of (Mars-) life on Mars.

To mitigate the potential for danger to astronauts and to Earth, as well as to avoid forward contamination of other bodies, planetary protection must be acknowledged as an important element for the success of human missions—and inclusion of planetary protection requirements should be considered a critical aspect of all human mission system and subsystems development.

Important Areas of Planetary Protection Research, Applications, and Implementation

A robust program of planetary protection, including forward contamination control, medical monitoring, spatial planning for human exploration, and precautions against back contamination, has been described in NASA and ESA-led studies (see Race et al, 2008), with an assumption that prior to human exploration there is a need for efforts to develop, rehearse and refine planetary protection controls. Effectively, these principles involve "defense in depth" and the continuous evaluation throughout a mission of the contamination status of the crew and the planetary environments (surface and subsurface) they will explore and utilize.

Topics for research, technology development, and testing include, but are not limited to:

a) Updating, Identifying, and Monitoring Potential Special Regions on Mars

It is anticipated that new information and understanding about martian environments and terrestrial microbes will continue to be gained through a robotic program of Mars exploration, and an eventual sample-return from Mars. In the future, more data about Mars environments should be available to help us understand and project where we might find Special Regions on Mars—places where Earth organisms might be able to replicate, and where (eventually) we may gain insights on the potential for indigenous life on Mars (c.f., Rummel et al. 2014).

On the top level, updated information on Mars Special Regions requires expanded knowledge of the limits of terrestrial microbial life, as well as the availability and action of water on Mars today, including specific features or depths in which places warm enough and wet enough might be found. Our understanding of the environmental limits to microbial reproduction on Earth, and the presence and availability of related resources on Mars, were updated by Rummel et al. (2014), but there are still major gaps in our understanding of life on Earth, let alone on Mars. If addressed, such information would add powerful insights into Mars astrobiology and clarify planetary protection issues associated both with Special Regions, themselves, and with the potential for Earth contamination to spread there.

Whereas Rummel et al. (2014) made a number of recommendations about knowledge required to better understand Special Regions on Mars, priority research needs are reproduced here:

- Understand the synergy of multiple factors that enable enhanced microbial survival and growth, and mechanisms that may allow for temporal separation in microbial resource acquisition and use.
- Investigations into microbial activity at low water activity—additional physiological studies on the limits to microbial survival and replication.
- Investigations into microbial activity at lower temperature limits for life.
- Further research into the excess ice and the mixtures of ice and salt observed at the Phoenix landing site.
- Extend the coverage of [resolution and near-surface penetration] of Mars radar surveys [beyond those by] MARSIS and SHARAD.
- Further investigations into caves on Mars. (Rummel et al., 2014)

b) Fundamental Knowledge on Microbial Limits of Life, and Human-Associated Microbial Diversity and Distribution:
Our understanding of environmental microbiology and extremophiles has expanded considerably, resulting in a greater awareness of the potential for the survival of terrestrial microbes in extreme environments, as well as the prospect for finding possible evidence of truly extraterrestrial life in other locations. It is essential to the proper implementation of planetary protection policy that habitability estimates for planetary environments be established conservatively, and that appropriate measures are taken to protect against contamination. Research on microbial diversity and adaptation to planetary environments are needed to inform planetary protection policies and their implementation.

Similarly, we have only recently recognized that humans themselves are a veritable scaffold upon which microbial ecosystems flourish. Powerful new analytical tools have become available to analyze and decipher such ecosystems and understand our human associated microorganisms (e.g., Stone 2009; Voorhies & Lorenzi 2016). Since these diverse microbial hitchhikers represent potential biocontaminants during human exploration of the solar system, it is important to understand them to the fullest—their identities, abundance, and distribution, as well as their potential for dispersal, survival and propagation as contaminants, and as markers in exploration environments, whether in habitat/work environments or exposed to the planet/moon itself.

Specific topics of relevance to the fundamental scientific understanding of human explorers in space include (but are not limited to):

- Development of a baseline inventory and understanding of human associated microbes, as relevant to the space environment;
- Studies of human associated microbes as potential contaminants, including their abundance, potential for release, and dispersal/survival/propagation during planetary exploration;
- Understanding human associated microbes as potential biomarkers of relevance, and their possible use as tracers of contamination;
- Contamination transport models (near and far-field);

- Studies to better understand the contribution of ambient space environments towards passive mitigation of forward contaminant risks (radiation, temperature, etc.).

c) *Testbeds for Technology Development and Operations*
The Moon in particular is considered to be an excellent potential testbed to develop planetary protection procedures and practices in an environment sufficiently harsh to prove an adequate challenge, but isolated from the overwhelming background contamination of the terrestrial biosphere. Because the Moon is currently recognized as being of interest for understanding prebiotic chemistry and the origin of life, but is not hospitable to contamination by Earth life, the only planetary protection constraint for operations on the Moon is the requirement to document activity. With no specific limits on contamination, the Moon can be an excellent place to test technologies developed for elsewhere in the solar system—in particular Mars. A coordinated lunar program addressing planetary protection issues could yield significant benefits (e.g., LEAG 2009) such as providing valuable ground truth on *in situ* contamination of samples; study lunar habitat/spacesuit competency, containment and leakage; and test operational procedures associated with successful planetary protection implementation on another planetary surface.

<u>Planetary Protection Implementation Measures for Human Exploration</u>
Through organized workshops and interdisciplinary information exchanges, the planetary protection community, working with engineering and systems experts, has been studying the implementation of NASA and COSPAR planetary protection policies (e.g., NASA 1999; Kminek and Rummel 2015) on numerous human associated activities and systems. Having established communication among these different groups for over a decade and a half, a series of planetary protection studies and workshops have helped identify important data needs, as well as priority R&D areas to support compatible astrobiology exploration with humans (cf., Criswell et al. 2005; Hogan et al, 2006; Kminek et al. 2007; NRC 2002b; NASA 2007; NASA 2015; etc.).

It is noteworthy that the science, technology and legal considerations for planetary protection during long duration human missions—especially for Mars—are significantly different than those used during the Apollo program, or for human missions involving the International Space Station or other platforms in Earth orbit that are not constrained by planetary protection considerations. Thus, it will be particularly important to continue discussions/interactions with space medicine, biomedical operations, and human/factors communities to ensure that these areas are incorporated into the up-to-date implementation of planetary protection for future exploration beyond LEO, and that the COSPAR principles and guidelines (see Kminek and Rummel 2015) for the human exploration of Mars can be met.

Draft Recommendation 1: NASA should continue to strengthen the link between life detection capabilities, identified or hypothesized Special Regions on Mars, and microbial survival as important topics in the understanding of the capability for this and other solar systems to support indigenous or terrestrial life. Such studies form an important part of basic astrobiology studies as well as astrobiological support to advanced exploration and astronomical studies.

Draft Recommendation 2: NASA should create an appropriately funded research and technology development activity to support the integration of a cross-cutting planetary protection activity into robotic and human space exploration, including connections to the astrobiology, space medicine, human factors, and the robotic- and human-mission operations communities, and should encourage exchange of information and future collaborative efforts aimed at feed-forward for both advanced robotic and eventual human space exploration.

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The Importance of UV Capabilities for Identifying Inhabited Exoplanets with Next Generation Space Telescopes

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ABSTRACT

The strongest remotely detectable signature of life on our planet today is the photosynthetically produced oxygen (O_2) in our atmosphere. However, recent studies of Earth's geochemical proxy record suggest that for all but the last ~500 million years, atmospheric O_2 would have been undetectable to a remote observer—and thus a potential false negative for life. During an extended period in Earth's middle history (2.0 – 0.7 billion years ago, Ga), O_2 was likely present but in low concentrations, with pO_2 estimates of ~ 0.1 – 1% of present day levels. Although O_2 has a weak spectral impact at these low abundances, O_3 in photochemical equilibrium with that O_2 would produce notable spectral features in the UV Hartley-Huggins band (~0.25 μm), with a weaker impact in the mid-IR band near 9.7 μm. Thus, taking Earth history as an informative example, there likely exists a category of exoplanets for which conventional biosignatures can only be identified in the UV. In this paper, we emphasize the importance of UV capabilities in the design of future space-based direct imaging telescopes such as HabEx or LUVOIR to detect O_3 on planets with intermediate oxygenation states. We also discuss strategies for mitigating against 'false positives'—that is, O_3 produced by abiotic processes. More generally, this specific example highlights the broad implications of studying Earth history as a window into understanding potential exoplanet biosignatures.

1. Introduction and Relevance

The search for life beyond our solar system is a prominent goal within the NASA astrobiology program, emphasized in both the 2008 Astrobiology Roadmap and the 2015 Astrobiology Strategy. The rapid evolution of exoplanet science from detection to characterization studies and the discovery of planets in the habitable zones of nearby stars underscores the timeliness of this effort. The nearest and best chance for identifying life on exoplanets will be provided by large (30-m class) ground-based observatories and future 10-m class space-based direct-imaging telescopes. While the James Webb Space Telescope (JWST), set to launch in 2019, will provide an unprecedented opportunity to characterize exoplanets through phase curves, secondary eclipse observations, and transit transmission spectroscopy, space-based direct-imaging characterization of terrestrial exoplanets will have to wait for dedicated observatories such as the LUVOIR or HabEx concepts (e.g., Mennesson et al. 2016; Bolcar et al. 2017). The science and technology definition teams (STDTs) for both concepts are convening now, and as was the case for JWST,

broad determination of the required instrument capabilities for these missions will be made many years and perhaps decades before their launch dates. It is therefore essential to accurately and swiftly identify the minimum capabilities for a direct-imaging observatory to accomplish top level objectives such as identifying inhabited planets (e.g., Stark et al., 2014).

The most commonly referenced biosignature gases are O_2 and its photochemical byproduct O_3, due to O_2's exclusive biological production on Earth through oxygenic photosynthesis and the strong thermodynamic and kinetic disequilibrium it produces in the atmosphere (Des Marais et al., 2002). Alternative biosignature gases, surface signatures, and overarching frameworks have been proposed and should remain an important part of the conversation (see reviews in Schwieterman et al., 2018; Meadows et al., 2018, Catling et al., 2018, Walker et al., 2018, and Fujii et al., 2018); however it remains important to fully benchmark and examine O_2/O_3 signatures. We assert that Earth's history tells us that O_3, best detected in the UV, is a more sensitive and consistent indicator of planetary scale photosynthetic life than O_2, thus minimizing the potential for false negatives. In section 2 below we review Earth's oxygenation history as context for this assertion. In section 3 we examine the remote detectability of O_2 and O_3 through that history, and we discuss mitigation against false positives in section 4. We summarize our recommendations in section 5.

2. Earth's Oxygenation History

Although molecular oxygen (O_2) currently represents ~20% of Earth's atmospheric mass, the amount of O_2 in our atmosphere has evolved dramatically over time. Indeed, for the vast majority of Earth history, atmospheric O_2 levels were orders of magnitude below those characteristic of the modern Earth. During Archean time (3.8 – 2.5 billion years ago, Ga), the preservation of non-mass-dependent sulfur isotope anomalies in marine sediments fingerprints atmospheric O_2 concentrations well below 10^{-5} times the present atmospheric level (PAL; Farquhar et al., 2001; Pavlov and Kasting, 2002; Claire et al., 2006). The disappearance of sulfur isotope anomalies from Earth's rock record at ~2.3 Ga points to a rise in atmospheric O_2 (Luo et al., 2016), but a number of geochemical archives suggest extended periods of very low atmospheric O_2 well after this initial rise (Lyons et al., 2014; Planavsky et al., 2014; Cole et al., 2016). It is thus possible that atmospheric O_2 has been well below ~1% of the modern value for as much as 90% of Earth's evolutionary history. Just as the Archean Earth has been presented as an analog for Earth-like exoplanets (Arney et al., 2016), the subsequent Proterozoic eon (2.5 – 0.5 Ga), comparable in duration, provides an additional template for understanding the potential atmospheric states of habitable exoplanets—and the fundamental controls that should determine the evolving redox states for many complex planetary systems.

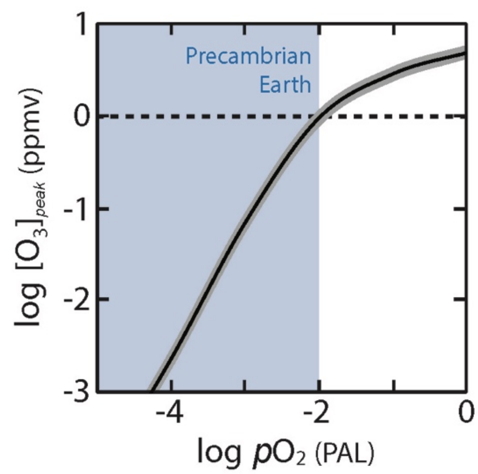

Figure 1 – O_3 abundance as a function of pO_2. *Calculation of peak stratospheric O_3 as a function of ground-level O_2 based results from Kasting and Donahue (1980). From Reinhard et al. (2017).*

3. Remote detectability of O_2/O_3 throughout Earth's history

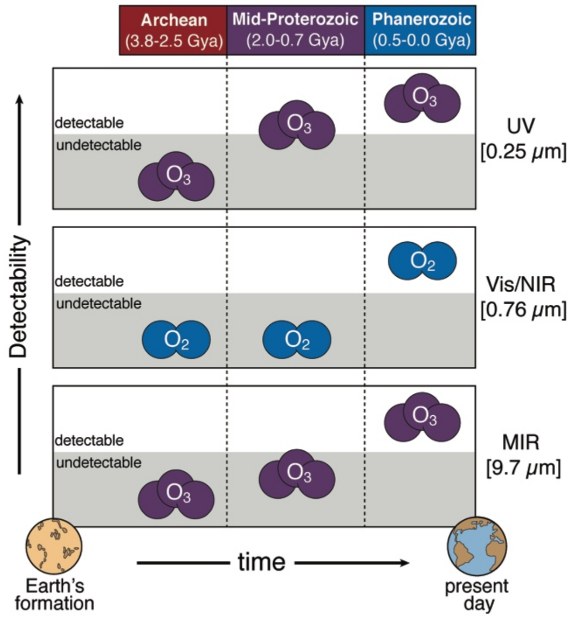

Figure 2 – Conceptual illustration of O_2/O_3 detectability in the UV, Vis/NIR, and MIR through Earth history. *This is a simplified representation of the spectral data in Figure 3. Adapted from Schwieterman et al. (2018).*

Molecular oxygen (O_2) shows no significant spectral features at mid-IR wavelengths but absorbs strongly at the Fraunhofer A and B bands (0.76 and 0.69 µm, respectively) and at 1.27 µm. The most prominent of these features is the Fraunhofer A band, but this feature is expected to have appreciable depth only at atmospheric levels of ~1% PAL or higher (Des Marais et al., 2002; Segura et al., 2003). As a result, direct detection and/or quantification of O_2 would have been extremely challenging for all but the last ~500 million years of Earth's history (Reinhard et al., 2017).

However, O_2 can be detected by proxy through searching for signs of atmospheric O_3. On Earth, O_3 is produced in the stratosphere through photolysis of O_2 and recombination of O atoms with ambient O_2 molecules through the Chapman reactions. In addition, photochemical models demonstrate that the atmospheric abundance of O_3 shows strong dependence on atmospheric O_2 at oxygenation states significantly below modern values (see Figure 1), with the result that atmospheric O_3 levels are potentially a very sensitive indicator of surface O_2 production on terrestrial planets with low to intermediate oxygen levels compared to those present today.

Ozone has a number of significant spectral features at UV, visible, and IR wavelengths. In particular, O_3 absorbs strongly within the Hartley-Huggins bands at ~0.35-0.2 µm and the Chappuis bands between 0.5 and 0.7 µm and shows an additional strong absorption feature at 9.7 µm. **From the standpoint of detection, it is the near-UV Hartley-Huggins feature centered at ~0.25 µm that is most important, because it is sensitive to extremely low levels of atmospheric O_3.** This feature saturates at peak O_3 abundances of less than ~1 ppmv, corresponding to a background atmospheric O_2 level of around 1% PAL (Reinhard et al., 2017). This critical observation indicates that it may have been possible to fingerprint the presence of biogenic O_2 in the atmosphere using the Hartley-Huggins feature of O_3 for, more than half of Earth's evolution, despite background O_2 levels that would have rendered direct detection of molecular O_2 extremely difficult. Figure 2 shows a schematic, simplified representation of the relationship between O_2 and O_3 concentrations and conservative estimated detection thresholds during three eons of Earth history (Archean, Proterozoic, and Phanerozoic/modern). Figure 3 displays simulated spectral observations of the UV Hartley-Huggins band, the O_2-A band, and the 9.7 μm O_3 band for upper and lower estimates of the concentrations of these gases during each eon (data obtained from Table 1 of Reinhard et al., 2017). From Figure 3 it is apparent that the **most sensitive indicator of atmospheric O_2 is the UV O_3 band**, which would have created a measurable impact on Earth's spectrum for perhaps ~50% of its history, versus ~10% for O_2.

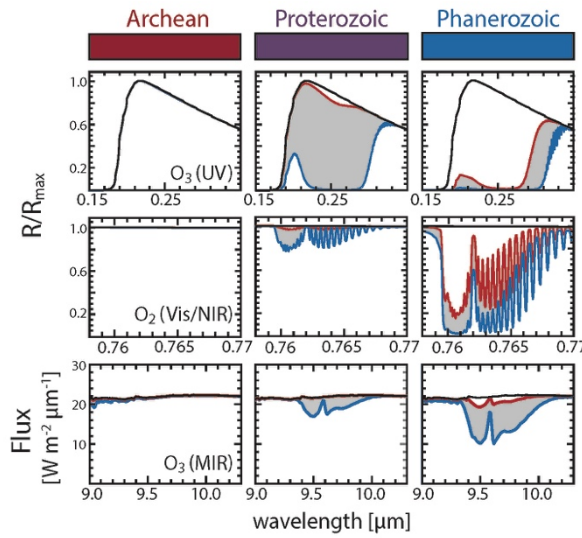

Figure 3 – Spectral features of O_2 and O_3 in the UV, Vis/NIR, and MIR. *Modeled planet spectra, at 1 cm^{-1} resolution, of the O_3 Huggins-Hartley band (0.25 μm), O_2-A band (0.76 μm), and 9.7 μm O_3 band at different geologic times assuming gas abundances informed by biogeochemical modelling and geochemical proxy constraints. Generated with the SMART radiative transfer model (Meadows & Crisp, 1996).*

4. Mitigating against 'false positives'

Recent work has illustrated several scenarios for abiotic buildup of O_2 and O_3 in planetary atmospheres, such as through extensive hydrogen escape or robust CO_2 photolysis (see reviews in Meadows, 2017 and Meadows et al., 2018). One relevant observation is that in most cases, potentially detectable abiotic O_3 is more easily generated than detectable O_2 (e.g., Domagal-Goldman et al., 2014). However, the most compelling scenarios for 'false positive' O_2/O_3 biosignatures concern planets orbiting M-dwarf stars, which possess extended pre-main sequence phases (enhancing the probability of hydrogen loss and O_2 buildup) and high FUV/NUV flux ratios (enhancing the photolysis rate of O-bearing molecules such as CO_2). Fortunately, however, inner working angle (IWA) constraints for direct-imaging telescopes will favor the angular separation of habitable zone planets orbiting early K, G, and F type stars, where the processes that may produce abiotic O_2/O_3 are disfavored. In addition, the absence of certain UV/Vis/NIR spectral indicators, such as O_4 and CO, can help rule out these 'false positive' mechanisms (e.g., Schwieterman et al., 2016). The most plausible mechanisms for abiotic O_2/O_3 in planets orbiting solar-type stars is steady H-escape from thin, water-rich atmospheres lacking in non-condensing gases (Wordsworth & Pierrehumbert, 2014), in which case blue-near-UV wavelength capabilities will be important for estimating atmospheric mass through characterizing Rayleigh scattering. This positive dynamic is enhanced further by the higher photospheric temperatures of FGK stars, generating more near-UV flux and thus greater S/N at wavelengths relevant to O_3 characterization. Of course, assessing the host star's UV spectrum would also help directly constrain plausible photolysis rates and the resulting potential for abiotic O_2/O_3 (e.g., France et al., 2016). Thus, 'false positives' can be successfully mitigated by both target selection and multi-wavelength characterization of planet and star, **which would be aided by UV capability**. Further, mitigating against O_2 'false negatives' requires UV, or less effectively, MIR wavelengths inaccessible to the HabEx/LUVOIR concepts.

5. Discussion and Conclusions

Remote observations of Earth would have failed to detect O_2 for 90% of its history if limited to optical and near-infrared wavelengths. In contrast, sensitivity to UV wavelengths would have allowed the detection of O_3, thus fingerprinting the presence of O_2 in our atmosphere for half its lifetime. There is no guarantee that habitable or inhabited exoplanets will be like Earth or recapitulate its atmospheric evolution, but if we take our planet as an informative example, **it is clear that detection thresholds of pO_2 > 1% PAL or higher could eliminate the potential for life detection on planets with intermediate oxygenation states (10^{-5} PAL < pO_2 < 1% PAL). Future work should carefully combine simulated planetary spectra and realistic instrumental performance for space telescopes with UV capabilities**. As a supporting proof of concept, the LCROSS mission has detected O_3 in remote observations of Earth (Robinson et al., 2014). Additionally, UV wavelengths provide more favorable IWA requirements than optical or near-infrared observations for both coronagraph- and starshade-based designs (Seager et al., 2015; Robinson et al., 2016), allowing a greater number of planets to be surveyed and a likely larger biosignature yield (e.g., Stark et al., 2014). Importantly, 'false positive' O_3 biosignatures can be mitigated through target selection and multi-wavelength planetary characterization (including the UV), while O_2 'false negatives' cannot be eliminated without the UV.

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Life Beyond the Solar System: Technology Needs

A Whitepaper in support of the Astrobiology Science Strategy

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I. Whitepaper Objective

In support of the Astrobiology Science Strategy, this whitepaper will attempt to outline the key technology challenges pertaining to the remote search for life in extrasolar planetary systems.

II. Science Questions

Thanks to NASA's Kepler space telescope, we now know that the Galaxy is teeming with planets. There is, on average, at least one exoplanet per star, and the majority of stars should contain an orbiting planetary system. We have learned that Earth-sized and "super-Earth" sized planets (between 0.5 and 2.5 earth radii) are the most commonly-sized planets, and while there are varying estimates on the frequency of such planets in the habitable zones of Sun-like stars, there is agreement that they are not rare (e.g. Fulton et al. 2017, Belikov et al. 2017). Consequently, we can move beyond the question of whether there are Earth-sized planets in the habitable zones of other stars, and we can now begin to ask (and answer) whether any of these planets harbor life.

The evidence for life on an exoplanet will most likely not be derived from a single measurement or observation, but rather will stem from a set of several measurements. This is because there are so many potential "false positives" for life that need to be ruled out - non-biological processes leading to perceived biosignatures. This results in a general drive towards as complete characterization of the planet and its stellar environment as possible, including: the spectral type and energy distribution of the host star, particularly in the ultraviolet; an understanding of the star's flare rates and coronal mass ejection history; a full inventory of the major gases in the planet's atmosphere; the physical properties of the planet's atmosphere such as characterization of the planetary surface in terms of the presence/absence of oceans, continents, and photosynthetic or other pigments; the orbital properties of the planet, in particular its semi-major axis and eccentricity; the mass, radius, and density of the planet; and the orbital properties and masses of other planets in the system.

Interestingly, all of these measurements fall into four kinds of observations: spectra of the planet, photometry of the planet, mass of the planet, and spectra of the star. But with specific interest in mature rocky planets in stars' habitable zone, only spectral measurements of stars can be acquired by instruments within the current technology state-of-art (SOA); the other three require technology development.

III. Key Technical Capabilities

To obtain the measurements listed in the previous section scientists need to develop the capabilities to do two very difficult things very well – 1) spectrally characterize the atmosphere and surface of Earth-like planets, and 2) measure their mass. These are what we refer to as desired key technical capabilities. Achieving these capabilities across a broad range of wavelengths, along with the existing capability to spectrally characterize stars, will allow astronomers to collect the necessary data.

There are three key technology areas requiring advancement to achieve these two capabilities:

- Direct imaging of exoplanets (so as to perform reflection/emission spectroscopy)

- Transit (absorption spectroscopy) / secondary eclipse (emission spectroscopy)
- Stellar reflex motion

IV. Technology Gaps

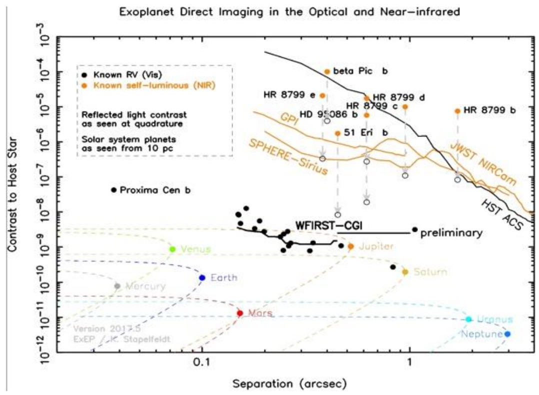

Figure 1: Contrast (ratio of planet brightness to host star brightness) versus apparent angular separation. For a larger version of this figure including a full caption go to exoplanets.nasa.gov/exep/technology/technology-overview/

NASA's Exoplanet Exploration Program (ExEP) identifies technology gaps pertaining to possible exoplanet missions and works with the community to identify and track technologies to prioritize for investment, and ultimately to close the gaps. These technologies are summarized in the ExEP's annually-updated Technology List (Crill & Siegler 2017a) and captured in detail in their Technology Plan Appendix (Crill & Siegler 2017b). A possible roadmap to mature these technologies is described in Crill & Siegler (2017c) The gaps in performance, as related to their technology areas, are:

<u>Direct imaging of exoplanets</u>

Starlight suppression for reflection (or emission) spectroscopy. Suppression of starlight in order to bring orbiting exoplanets into view requires either starlight occultation or nulling. Those are the only two approaches known. Starlight occultation technologies include both internal (coronagraph) and external (starshade) approaches and have continued to progress this decade largely motivated by the 2010 Decadal Survey's number one medium-scale size recommendation - developing the technologies to enable the imaging of rocky planets in the next decade. NASA chose the simpler single room-temperature telescope observing at short wavelengths over the more complex multiple telescope, cryogenic, formation flying architecture that the long wavelength observations starlight nulling would have required.

Ground-based telescopes with coronagraphs, even next generation instruments on future 30 m-class telescopes, are expected to be fundamentally limited to 10^{-8} contrast sensitivities due to the residual uncorrected errors from atmospheric turbulence correction (Stapelfeldt 2005; Traub & Oppenheimer 2010). WFIRST's technology demonstration coronagraph will be the first high-contrast coronagraph in space possessing wavefront-correcting optics, such as a low-order wavefront sensor and deformable mirrors, to achieve contrast sensitivities between 10^{-8} and 10^{-9}. WFIRST and its 2.4 m telescope is planned to launch in the mid-2020s. To observe an Earth-size exoplanet orbiting in the habitable zone of a Sun-like star, however, would require sensitivities to contrast ratios of 10^{-10} or better (see Fig 1); large super-Earths could be slightly more favorable. This is 1-2 orders of magnitude more demanding than WFIRST's expected performance and 2 orders more than future ground-based telescopes.

Coronagraphs with little to no central obscuration will have the highest likelihood to achieve the 10^{-10} contrast goal while simultaneously achieving high throughput. The Hybrid Lyot coronagraph achieved $6\text{x}10^{-10}$ contrast at 10% bandwidth (Trauger et al. 2011). The Decadal Survey Testbed, an ExEP facility for testing next-generation coronagraphs, is being commissioned in the spring of 2018 to advance performance to better than 10^{-10}. Future large space telescopes are very likely to have segmented apertures with secondary mirror obscurations. To address the challenges in achieving the contrast goals while maintaining high throughput, the ExEP Segmented Coronagraph Design & Analysis study was commissioned in 2016 to work with leading coronagraph designers. At the time of this writing there are about a couple candidates on the path to meet the requirements. If successful, the masks and optics for these designs will be fabricated and tested in multiple testbeds before the end of the decade. A coronagraph solution to imaging exo-Earths in their stars' habitable zone appears to be on track.

The starshade is currently being advanced under an ExEP technology development activity. While a full-scale starshade has never been demonstrated, a preliminary assessment (Seager et al. 2015) has developed design models predicting better than 10^{-10} contrast and a sub-scale validation demonstration is far along. However, to test the diffraction regime expected in space (i.e. flight Fresnel number) and operating within a practical-sized testbed (77 m), the demonstration is being conducted with only a 25 mm starshade (the separations between the "spacecraft" increase with the square of the starshade radius so testing large sizes require very large testbeds). To test the robustness of the optical models, intentions are to conduct additional suppression testing at longer wavelengths and more than one starshade size.

The scattering of Sun light off the starshade's petal edges is an important design factor and materials that are sufficiently thin, low-reflectivity, and malleable for stowage are being investigated. The starshade also requires a precise and stable structural deployment from a stowed configuration that is unique to previous NASA missions (< 1 mm petal positioning error). However, there does not appear to be any show-stoppers for a starshade to be mechanically designed to deploy to this tolerance. The starshade appears to be on a path to reach TRL 5 in the early part of the next decade and be ready for a potential rendezvous mission with WFIRST (pending recommendation by the 2020 Decadal Survey).

Contrast stability. Due to the extremely low rate of photons from distant exoplanets (in the range of about a photon per minute(s) in the case of the WFIRST coronagraph), achieving spectroscopy at a sufficient signal-to-noise ratio will require long integration times. The extreme starlight suppression must be maintained as the space observatory experiences drifts (both thermal and dynamic changes) during the integration. Large segmented telescopes will particularly be challenged by the need to achieve a stable back-structure and maintain a large number of individual segments as a single paraboloid. Lastly, spacecraft disturbances such as those initiated by reaction wheels must be dampened before reaching the coronagraph.

In the case of coronagraphy, error budgets for wavefront error stability range typically between 10-100 pm rms for a telescope and instrument system (Nemati et al 2017). This is 1-2 orders of magnitude more demanding than what has been demonstrated in space or in the lab. On-going analyses being conducted by the HabEx and LUVOIR study design teams will best determine the likelihood of these telescope systems meeting the very demanding wavefront error stability requirements.

In the case of a starshade-only mission, telescope stability requirements are significantly looser and do not exceed the SOA. Solutions for sensing and alignment control between the two spacecrafts have been developed and subscale demonstrations are being conducted in the lab.

Detection sensitivity. Even after suppressing the starlight to achieve the demanding contrast sensitivities and maintaining the required wavefront error stability, the light from the exoplanets must still be detected. The low flux of the targets requires a detector with read noise and spurious photon count rate as close to zero as possible, and that maintains adequate performance in the space environment. The SOA is dependent on the wavelength band but detectors must perform at or near the photon counting limit in the near-UV, the visible band, the near-IR, and the mid-IR. Across this wavelength range, the SOA detectors are semiconductor-based devices. WFIRST's electron multiplying charge coupled device (EMCCD) detectors have achieved adequate noise performance in the visible band, though longer lifetime in the space radiation environment is desirable. Similar EMCCD devices, with delta doping, may already have adequate performance in the near-UV. HgCdTe detectors are the SOA in the NIR. JWST/MIRI's detectors are expected to establish the SOA in mid-IR detection sensitivity, and future direct imaging is likely to require detectors that exceed it. It is likely that the detection sensitivity gap can be closed in the next decade, as a range of choices are close to meeting the requirements.

Angular resolution and collecting area. Large space telescopes offer many benefits in the determination of exoplanet habitability. Improved spatial resolution allows for a larger exoplanet yield, particularly those in the habitable zones of nearby stars. The larger collecting area also enables higher spectral resolution to better define molecular features as well as overall improved detection sensitivity. A larger telescope also better rejects the extended diffuse brightness of exozodiacal light that could obscure exoplanets. The largest monoliths flown in space are the 2.4 m Hubble Space Telescope, optimized for visible and UV astronomy, and Herschel's 3.5 m telescope, optimized for the far-IR. The James Webb Space Telescope will establish the SOA in space telescopes with a 6.5 m primary mirror made up of 18 co-phased hexagonal beryllium segments. Current mission concept studies range from 4 m monoliths to 15 m segmented telescopes.

Large glass monoliths have been commonly fabricated for ground-based telescopes. If future heavy-lift launch vehicles like the Space Launch System become a reality then the opportunity for a 4 m-class monolith becomes a possibility. Large monoliths will advance exoplanet science but will not directly lead to subsequent larger telescope architectures (> 10 m). One-meter class silicon carbide and glass segmented mirrors have fabrication heritage and appear to be promising options if the design teams can show there is sufficient control authority to meet the contrast goals.

<u>Transit/secondary eclipse spectroscopy</u>

Spectroscopic Sensitivity. To enable precise transit or secondary eclipse spectroscopy, the detector response must exhibit photometric stability over the time scales of a transit, typically hours to days. Spitzer/IRAC has achieved photometric stability of order 60 parts per million on transit time scales. JWST/MIRI is expected to achieve stability between 10-100 ppm. A stability of 5-10 ppm in the mid-IR is needed in order to measure the atmospheres of Earth-sized planets transiting nearby M-dwarfs. Astrophysical limits to this technique due to stellar activity need to be quantified.

The path to close the technology gap in transit spectroscopy is currently not known. First, astrophysical limits should be examined further to find likely fundamental limits to stellar stability. The sources of instability in detector/telescope systems must be studied to determine where future technology investments will be most effective. Photometric instabilities of a mid-IR detector system may be driven by fundamental detector materials properties, cryogenic detector readout circuitry, or other instabilities in the system. This should be done along with modeling the on-orbit calibration, which will mitigate the detector requirements to some level.

Valuable lessons will be learned from performing these measurements with JWST/MIRI in the early 2020s.

Stellar reflex motion

Radial stellar motion sensitivity. Radial velocity (RV) measurements of the reflex motion of a star can be a way to infer the minimum mass and orbital parameters of planets orbiting the star. The HARPS instrument has recently achieved 40 cm/s precision (Feng et al. 2017). The next generation of ground-based RV instruments coming online in the next 1-2 years are expected to achieve 20-30 cm/s instrumental sensitivity per measurement. The reflex motion of a Solar-mass star due to an orbiting Earth-mass planet at 1 AU is ~10 cm/s over 1 year, and both measurement and systematic errors must be kept below that.

The biggest uncertainty in closing this gap is understanding the astrophysical limits due to natural stellar jitter. At this point the path forward to achieving 1 cm/s sensitivity and closing the gap is unclear but may be better understood upon completion of NASA-chartered probe study, and through experience at mitigating systematics errors in ground-based RV instruments measurements.

Tangential Stellar Motion Sensitivity. By performing sensitive astrometry of a star over time, the mass and orbital parameters of orbiting exoplanets can be measured. GAIA's initial data release achieved a typical 300 microarcsecond position error, but GAIA is expected to achieve 10 microarcsecond sensitivity in the positions of many stars in subsequent data releases, sensitive enough to reveal many Jupiter-mass exoplanets. A precision of 0.3 microarcsecond per measurement is needed in order to enable the detection of Earth-mass planets at a distance of 10 pc.

The path to closing this technology gap in astrometry is not clear. It is possible that astrophysical limits due to variable stellar surface structure may prevent astronomers from reaching this precision. The inherent instabilities of stars needs further understanding and sources of instrument instability and the ability to calibrate them using techniques such as interferences fringes or diffractive pupils should be modeled.

V. Conclusion

The existing technology gaps needing to be bridged to provide astronomers the necessary capabilities to obtain the key measurements are, in some cases, 1-2 orders of magnitude from the SOA or involve performances never demonstrated. The technologies being developed to close these gaps have been identified and are being advanced. They are currently at various degrees of readiness. These technologies are summarized in the ExEP's annually-updated Technology List (Crill & Siegler 2017a) and captured in detail in their Technology Plan Appendix (Crill & Siegler 2017b). A life-finding large mission recommendation by the 2020 Decadal Survey would be required to prioritize, focus, and accelerate technology development in the next decade to enable a launch in the 2030s.

References can be found at the following URL:
https://exoplanets.nasa.gov/internal_resources/774_References_for_Astrobiology_Technology_Whitepaper.pdf

A Better Biologically Informed Manned Mission to Mars

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A Better Biologically Informed Manned Mission to Mars

A better biologically informed manned mission to Mars will increase the probability of the success of the mission in finding past and/or present life on Mars.

An important scientific topic of research omitted from the NASA Astrobiology Strategy 2015, and which has seen significant scientific progress and advancement since publication is the collection and study of Ice Meteorites. Specifically, the Port Sanilac Ice Meteorite and the Pullman Ice Meteorite. Both Ice Meteorites contain extraterrestrial biology. (Photos 2 thru 6)

Promising key research goals in the field of the search for signs of extraterrestrial life have been made since the publication of NASA Astrobiology 2015.

Many key scientific questions in astrobiology as they pertain to the search for extraterrestrial life in our solar system can now be answered. This new information can be useful in better informing the crew of a manned mission to Mars as to what species of biology they may possibly find or encounter, whether past or present. A better informed crew will know where and why to explore specific locations on Mars.

The Port Sanilac Ice Meteorite fell to Earth at 4:41 pm, the 9th of December 2015. The fall of this ice was witnessed by three persons. Its impact was recorded by a nearby security camera. The published paper on the study of this Ice Meteorite “ The Port Sanilac Ice Meteorite, The First Recognized Ice Meteorite With Aquatic and Ice Biology” can be found. (ref. 1)

The Pullman Ice Meteorite fell to Earth on the 12th of March, 2000. Three pieces of this ice was collected by this author and keep frozen at negative 24 degrees C. A gas analysis of this ice performed in 2001 matches NASA’s gas analysis performed in 2008. This gas analysis also includes the higher water vapor content of the water vapor cloud found at the South Polar Region (SPR) of Enceladus. The published paper on the partial study of this Ice Meteorite “The Origins of Megacryometeors: Troposphere or Extraterrestrial?” Can be found. (ref. 2)

The water of both of these Ice meteorites is frozen hydrothermal water, with the right size nano-silica indicating that it is in fact hydrothermal water. These frozen water Ice Meteorites could not have formed in Earth’s atmosphere. Both Ice Meteorites contain aquatic biology not found in Earth’s atmosphere. Both Of these Ice Meteorites contain gas bubbles that could not have formed in Earth’s Atmosphere. The Pullman Ice Meteorite contain small solid objects imbedded within the interior, three of which are small stones, again not found in Earth’s atmosphere.

This author saved some of the meltwater from the Pullman ice fall using five small glass vials and double sealed and stored them in a cigar box. I made sure that no visible particles or material was included in these vials, just water. Recently, I examined these vials. I found that the water in two of the vials had been completely consumed, desert dry. There was no way for the water to have leaked out or to have evaporated with the double sealing in place. The water was consumed, perhaps as a source of electron energy needed for metabolism, and gas and a biomass left behind. In 2 other vials, the water was mostly consumed with a gas and a biomass left behind. In the 5th vial, some of the water was consumed and a gas and a biomass left behind. This 5th vial was double sealed in a different way than the other 4 vials. The 5th vial was sealed like a bottle of fine wine, a silicon stopper wired tight. (photo 1) There are two different species of biology in these five vials, in the first four vials the biomass is brown and appear to be rod like filaments, in the 5th vial the biomass is carbon black and appears to be a colony of sphericals. I believe that the biology in these vials is methanogenic biology and the gas is methane. The biomass in vial #5 is found thru-out both the Port Sanilac ice and the Pullman ice and the aquatic biology is simular in both ices.

Should the gas be methane, then the biomass at the bottom of the vial will be methanogenic biology, this will prove conclusively that the water is oxygen free anaerobic water and that this ice could not have formed in Earth's atmosphere.

A complete study of the biology and the material in these two Ice Meteorites will answer key scientific questions in the field of Astrobiology as they pertain to the search for life by the crew of a manned mission to Mars. The Mission will be better informed and better prepared. This will increase the probability of success for the mission in finding a third location of life in our Solar system.

To this end, this author proposes that NASA and/or NASA's Space Studies Board acquire both Ice Meteorites for a more complete and in-depth study of the biology and material contained in these Ice Meteorites.

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Ref. 1) "The Port Sanilac Ice Meteorite: The First Recognized Ice Meteorite with Aquatic and Ice Biology" Journal of Cosmology 2017, volume 26, pp 14152-14176

Ref. 2) "The Origins of Megacryometeors: Troposphere or Extraterrestrial?" Journal of Cosmology 2015, volume 19, pp 70-86

Photo 1) Pullman Ice Meteorite meltwater #5 vial

Photo 2) Pullman Ice Meteorite Biology

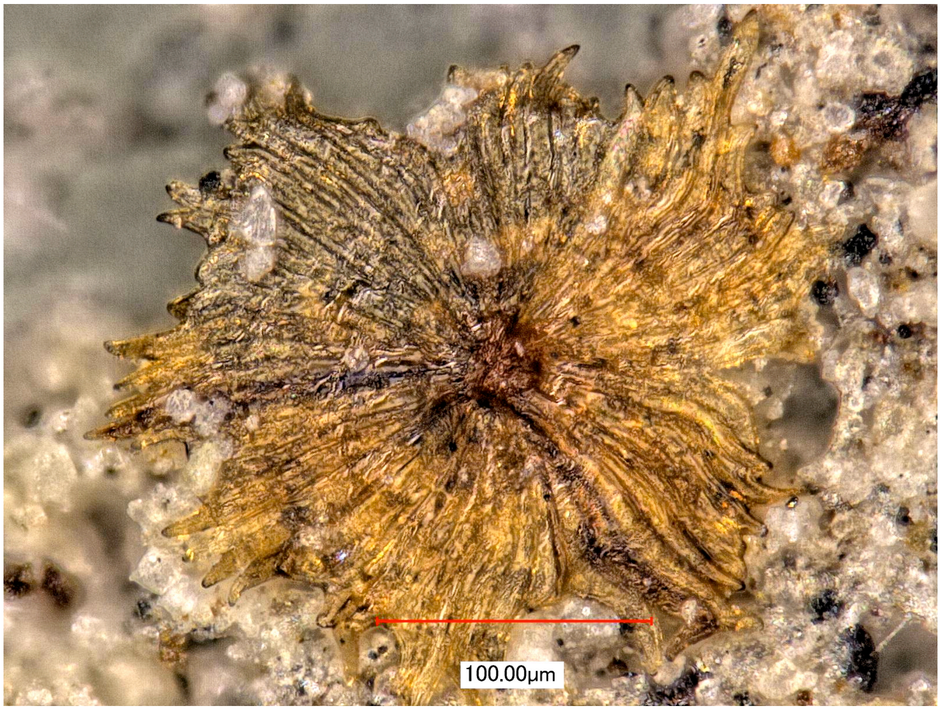

Photo 3) Pullman Ice Meteorite Revived Biology

Photo 4) Port Sanilac Ice Meteorite Biology

Photo 5) Pullman Ice Meteorite Biology

Photo 6) Port Sanilac Ice Meteorite Biology

Three Versions of the Third Law: Technosignatures and Astrobiology

Astrobiology Science Strategy for the Search for Life in the Universe
National Academies of Sciences, Engineering, and Medicine - White Paper January 2018

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The Lead author and Co-authors represent the following SETI-related organizations whose many members have contributed to, or commented on, this white paper. Since these groups may be unfamiliar to the reader, a brief description and URL's are given below for each organization.

[1] The Center for SETI Research was one of the original Centers established in 1984 when the 501(c)(3) SETI Institute was founded with a mission is to explore, understand, and explain the origin and nature of life in the universe, and to apply the knowledge gained to inspire and guide present and future generations. We have a passion for discovery, and for sharing knowledge as scientific ambassadors to the public, the press, and the government. https://www.seti.org/aboutus
[2] The Science Advisory Board of the SETI Institute has 13 members from academia, MBARI, USGS, and the Vatican Observatory, and provides scientific guidance to the Board of Trustees. https://www.seti.org/seti-institute/SETI-Institute-science-advisory-board
[3] The Berkeley SETI Research Center serves as the organizational entity for searches for advanced extraterrestrial life at UC Berkeley, including the Search for Extraterrestrial Radio Emissions from Nearby Developed Intelligent Populations (SERENDIP), SETI@Home, Astropulse, public outreach activities, and Breakthrough Listen. http://seti.berkeley.edu
[4] The Breakthrough Listen Initiative has established an Advisory Committee to provide guidance on the scientific and technical aspects of the 10-year, privately funded, observational program to find evidence of ETI. Its 27 members are drawn from academia, observatories, non-profits, and industry from this country as well as China, Australia, the UK and Austria. https://breakthroughinitiatives.org/leaders/1
[5] The Permanent SETI Committee is the current incarnation of a committee established first under the auspices of the International Academy of Astronautics in 1974 to facilitate the global exchange of information about SETI programs. https://iaaseti.org/en/
[6] The International SETI Collaboration was started in 2017 as an ad hoc community, utilizing modern video conferencing tools to enable monthly opportunities for technical information exchange. (No URL available)

Summary
Not knowing exactly what to look for, Astrobiology should embrace, and prioritize, all scientifically plausible and technologically feasible search strategies for both biosignatures and technosignatures. There is no scientific justification for excluding SETI, or any other technosignature modality, from the suite of astrobiological investigations. Arguments based on political sensitivities or apparent access to other funding sources are inappropriate. In this white paper, we argue for a level playing field.

The Third Law
In 1973 Arthur C. Clarke (British engineer turned science fiction author) formulated his three laws [1]

1. When a distinguished but elderly scientist states that something is possible, they are almost certainly right. When they state that something is impossible, they are very probably wrong.
2. The only way of discovering the limits of the possible is to venture a little way past them into the impossible.
3. Any sufficiently advanced technology is indistinguishable from magic.

This third law has dominated dedicated searches for technosignatures ever since, although our research methodology is rigorous, not 'magic'. The search for extraterrestrial intelligence is instead a search for alien technologies that are modifying their environment in ways that can be sensed remotely; e.g., artifacts within our solar system, electromagnetic radiation, great feats of astroengineering, and even industrial pollution.

Some of the 'magic' may be quite difficult to detect, and unrealistic. Karl Schroeder (Canadian futurist and science fiction author) has suggested a second variant of the third law; Any sufficiently advanced technology is indistinguishable from *Natu*re [2]. Great longevity requires sustainability. "In the Great Silence [the failure of decades of SETI projects to detect a signal], we see the future of technology, and it lies in achieving greater and greater efficiencies, until our machines approach the thermodynamic equilibria of their environment, and our economics is replaced by an ecology where nothing is wasted." [3]

Finally, when conceiving the potential perils of superintelligent singletons that are insufficiently boxed or constrained, or given goals that are not well thought out [4], one can imagine that Nick Bostrom (Swedish philosopher and futurist) **might** construct the following version of the third law; Any sufficiently advanced technology is indistinguishable from paper clips. [If such an entity were instructed to make one million paper clips, it would never be 100% sure it had achieved its goal and thus would transform all available matter into paper clips and paper clip manufacturing tools or into whatever its goal specified.]

In seeking to discover evidence of any of these versions of the third law, astrobiology could succeed. Unfortunately, without knowing the answer in advance, we do not have a foolproof way of deciding what strategies for the detection of technosignatures make the most sense. Therefore, until we have more information, we should employ those strategies that have sufficient sensitivity to produce significant null results or a positive detection.

We have now discovered that there are more planets than stars, at least in the Milky Way Galaxy, and we are seriously studying the life strategies that allow extremophiles to populate almost every environmental niche on this planet. Even though a 2007 NRC report on weird life [5] concluded that biosolvents other than water might be possible, the astrobiology community has continued defining potentially habitable planets, and their habitable zone, in terms of liquid water. That definition is useful because it acknowledges our limited capability to study other possibilities. We don't know how to find weird life, and we might not recognize it if we did; on Earth or beyond. Some scientific science fiction writers have done a credible job of imagining life forms that were not initially recognized as such; think of Fred Hoyle's Black Cloud [6], or Robert Forward's 'Cheela' living at accelerated speeds on the surface of a neutron star [7], or Arthur C. Clarke's aquatic Europans [8]. These last are something that the astrobiology community is actively planning to seek out in the near future. If they are there, will they be recognizable? Will they be detected by any of the life detection tools we will send; tools that are inevitably going to be based on life as we know it? As the chemosynthetic communities surrounding Earth's black smokers remind us, life on the ocean floor need not all be microscopic, and underwater camera systems and lights will be valuable tools on Europa once we get the capability to deploy them there. In other environments, tools that recognize patterns of technology might be even more valuable.

According to Sagan, Thompson, Carlson, Gurnett, and Hord in their 1993 Nature paper, when the Galileo spacecraft did a flyby of Earth, utilizing all its scientific instruments, "one of the strongest pieces of evidence for life (indeed intelligent life) on Earth was the presence of narrow-band, pulsed, amplitude-modulated radio transmission." [9]**.** And yet this is precisely the type of evidence that the current **2015 NASA Astrobiology Strategy** specifically refuses to acknowledge under the umbrella of astrobiology: "While traditional Search for Extraterrestrial Intelligence (SETI) is not part of astrobiology, and is currently well-funded by private sources, it is reasonable for astrobiology to maintain strong ties to the SETI community." [10]. This is an arbitrary distinction that artificially limits the selection of appropriate tools for astrobiology to employ in the search for life beyond Earth, one that it is not supported scientifically. The science of astrobiology recognizes life as a continuum from microbes to mathematicians. It is time to remove this artificial barrier, and to re-integrate the community of all those who wish to study the origin, evolution, and *distribution* of life in the universe.

A Brief History

Until 1993, when Sen. Bryan (D–Nev.) terminated FY94 funding for NASA's High Resolution Microwave Survey, and SETI became a 4-letter S-word at NASA Headquarters, the disciplines of Exobiology, Bioastronomy, and finally Astrobiology all took a catholic view of life and its co-evolution with its host world. Post-HRMS termination, other small NASA SETI programs were also shut down [11]. The NSF included a prohibition against funding for SETI in its annual, agency-wide, *NSF Guide to Programs*. That language remained in place until actions by Congress caused NSF Director Rita Colwell to remove it in 2000 [12].

Indeed SETI, at least by that name, has always been a political lightning rod, and that has resulted in a checkered history of inclusion in, or exclusion from, the series of astrobiology roadmaps leading up to the current **2015 NASA Astrobiology Strategy**. In the precursor **Astrobiology Roadmaps of 1998, 2003, and 2008**, SETI was addressed (or ignored) under Goal 7, "Determine how to recognize the signatures of life on other worlds ". This Goal and its attendant objectives have evolved over time as astrobiology has matured, technologies have improved, and the political climate has changed. Table 1 is an attempt to summarize the status of observational SETI research in each precursor document.

SETI's unmentionable, post-termination status did not change until the door was cracked open during a 2001 hearing on Life in the Universe, held by the Subcommittee on Space and Aeronautics. In reply to a direct question from the Subcommittee, NASA Associate Administrator Ed Weiler responded, "NASA is no longer prohibited by any congressional language from considering or funding SETI research, so SETI is currently eligible and considered fairly under peer review for NASA opportunities." [13]

Table 1: Treatment of Technosignatures and SETI in Astrobiology Roadmaps/Strategies

Document	Biosign.	Technosign.	SETI	Action
1998 Roadmap	√	—	—	**Goal 7** envisioned only chemical biomarkers or remote biosignatures
2003 Roadmap	√	√	√	**Goal 7** added on "Thus, although technology is probably much more rare than life in the universe, its associated biosignatures perhaps enjoy a much higher "signal-to-noise" ratio. Accordingly, current methods should be further developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations."
2008 Roadmap	√	√	√	**Goal 7** was changed to "Determine how to recognize signatures of life on other worlds and on early Earth. Identify biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify biosignatures of distant technologies." The **background section for Goal 7** stated "Accordingly, current methods should be further developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations." **Objective 7.2** expanded with "Learn how to identify and measure biosignatures that can reveal the existence of life or technology through remote observations."
2015 Strategy	√	√	**X**	**Page 76** "… we should also be aware of the possibility of planets with anomalies that are the result of technological activities. Much attention has focused on which qualities of terrestrial life might be universal, and therefore relevant to the search for biosignatures; similarly, it is worth considering which aspects of technological civilization might be universal, how such qualities should be expected to affect the observable aspects of a planet, and how they might be discernible from other biosignatures." However, on **Page 150** "While traditional Search for Extraterrestrial Intelligence (SETI) is not part of astrobiology, and is currently well-funded by private sources, it is reasonable for astrobiology to maintain strong ties to the SETI community."

√ indicates that this activity was supported by the document
— indicates that the document was silent regarding this activity
X indicates that the document explicitly excluded this activity

While roadmaps and strategic plans are of great importance, it is NASA's funding vehicle, the annual ROSES call for proposals, and the less frequent NAI CAN opportunities that define the playing field of the possible. These have been inconsistent with respect to searches for technosignatures and SETI. Operating under the guidelines of the 2008 Astrobiology Roadmap, Table 2. shows what the opportunity space has been.

Table 2: Treatment of Technosignatures and SETI in NASA ROSES and NAI CAN calls.

Document	Biosign.	Technosign.	SETI	Opportunity
ROSES 2008	√	√	√	C.17 (Astrobiology, Exobiology, Evolutionary Biology) is silent on SETI, but E.3 (Origins of Solar Systems) solicits "… detection and characterization of other planetary systems including those that may harbor intelligent life."
ROSES 2009	√	√	—	E.3 stated that, "the research goals of proposals aimed at identification and characterization of signals and/or properties of extrasolar planets that may harbor intelligent life previously included in this program are covered by the Astrobiology: Exobiology and Evolutionary Biology (Appendix C.17) and Astrobiology Science and Technology Instrument Development (ASTID, Appendix C.19) program elements. While C.17 and C.19 remained silent on SETI.
ROSES 2010 & 2011	√	√	√	C.17 under the program element *Evolution of Advanced Life* now includes "Proposals aimed at identification and characterization of signals and/or properties of extrasolar planets that may harbor intelligent life are also solicited."
ROSES 2012				There was no call for C.17 that year
ROSES 2013	√	√	**X**	C.17 explicitly excluded SETI proposals. "Proposals aimed at identification and characterization of signals and/or properties of extrasolar planets that may harbor intelligent life are not solicited at this time."
ROSES 2014 - 16	√	√	**X**	This same exclusionary language persisted from ROSES 2013 through ROSES 2016, and C.17 was restructured into C.5 (Exobiology).
ROSES 2017	√	√	**X** **?**	C.5 is confusing. Under the program element *Evolution of Advanced Life*, the same exclusionary statement persists. But under the element *Biosignatures and Life Elsewhere,* "Additionally, research focused on understanding or characterizing nonradio "technosignatures" from extrasolar planets that may harbor intelligent life are included in this area."

√ indicates that this activity was supported by the document
— indicates that the document was silent regarding this activity
X indicates that the document explicitly excluded this activity

Consistent with the SETI-friendly **2008 Astrobiology Roadmap**, the **NAI CAN-5** issued that year stated "The [2008] Roadmap lays out Astrobiology investigations in a continuum from the study of the biogenic compounds during solar system formation through the detection of technologies indicating extraterrestrial intelligent life, with particular attention to the effects of interstellar and interplanetary phenomena on life on Earth—its origins, evolution, and the extent of global changes and destruction that have been caused by Earth-impacting objects." An NAI Team whose proposal contained a SETI component was in fact selected that year.

As the concept of the Anthropocene has gained credence, it has become more firmly established that the search for technosignatures is a legitimate approach to satisfying **Goal 7**, and scientifically what has been called SETI is one such technique. A 2016 paper by N. Cabrol [14] invited suggestions from a multi-disciplinary audience for innovative new ways to detect intelligent life-as-we-don't-yet-know-it. White papers responding to that invitation have been reviewed and will form the basis for a workshop in March 2018, the results of which will be shared with the Space Studies Board Astrobiology Science Strategy for the Search for Life in the Universe Committee. The Advisory Committee for the Breakthrough Listen SETI effort has also established a subcommittee to consider 'other methods' of detecting ETI. SETI is expanding its toolkit.

Conclusion

It is time that we end this scientific schizophrenia. It is of course reasonable for a funding agency to elect not to fund any given proposal, but it is unscientific to exclude clearly related proposals from consideration. Historical politics or a perceived (but unverified) funding status from other sources should not enter into an estimation of the scientific value of an approach. All versions of 'The Third Law' (seemingly "magical" technology, husbanded nature, and machine-driven monotony) may suggest research directions that are radically different. One or more of those may move the field of Astrobiology forward in unexpected, and productive, ways.

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[11] Private communication in memo from John Rummel to Mary Voytek "SETI in Astrobiology" Feb 2017

[12] Reproduction of letter from Office of NSF Director to Office of Lamar Smith dated April 24, 2000.

[13] As down loaded 1/5/18 from http://commdocs.house.gov/committees/science/hsy73839.000/hsy73839_0f.htm page 132.

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Unexpected features in the distribution of counts of giant planets could have an influence the numbers of potentially habitable planets

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Abstract
We present how newly found unexpected features in the distribution of counts of planets by period could influence the numbers of potentially habitable worlds. These features mean that there are fewer planets with periods over 500 days, with more planets having periods below this. Whether these features extend down to lower mass planets than those currently being survey is an important question. We separately address (topic 2) how striving for completeness in including marginalized members of the science community. Characterizing the features in the parameters of planets by period is essential to provide the best feedback to modeling planet formation.

Introduction
The distribution of exoplanets in and near the habitable zone is far from uniform in log period, at least for planets with enough mass to have been found by radial velocity. The likelihood of a distribution that changes by period should be considered when considering how many habitable planets are potentially observable.

We have found that for planets with high enough mass to have been found by radial velocity, that the distribution in planets in the metal-rich majority of systems that are ``sunlike'' (with log surface gravity greater than 4) has a bimodal pileup with a gap of few planets.

We promote the importance of conducting survey using radial velocity to characterize the distribution of planets of lower masses.

The unexpected discovery of a double-peaked structure in the counts of the main pileup of exoplanets shows that there must be important aspects of planet formation that we still do not understand.

This gap shows that the outer habitable zone is surprisingly underpopulated of giant planets, because of there being a gap in counts of such planets among unevolved single stars with the same or higher metallicity of the sun. This represents at least 60% of the planets of unevolved stars, or higher depending on how much the gap affects planets of stars with stellar companions. Whether this gap extends down to lower mass planets is an important question for astrobiology because it could indicate fewer potentially habitable planets in the colder part of the habitable zone.

We describe the gap below. We summarize to the analyses of showing that it is extremely unlikely that this gap is either due to a random fluctuation or to observational effects.

Piling up of different populations

We show in Figure 1 the histogrammed counts of all the objects found by the radial velocity method (RV), black line, with periods up to 5000 days. We use data from exoplanets.org (Han et al. 2014) that has 434 planets found by radial velocity (RV) by 2016 that have a full set of parameters with periods up to 5000 days.
This shows how the combined counts increase to a peak with their highest densities at periods in between several hundred days to a little over a thousand days. The combined counts of all objects found by RV, as the counts versus log period as shown in Figure 1, forms a pileup at periods longer than 100 days. We call this pileup the ``main pileup'' because in contrast to the smaller pileup at shorter period, the region past 100 days contains 313 of the 434 objects found by RV before 2017 with periods from 1 to 5000 days.

The main pileup is moderately irregular, with a dip at periods under one thousand days. When this dip is seen in the combined counts, it might appear as if it were a statistical fluctuation. It is only when the selection of planets hosted by single sunlike (that is, unevolved with log g < 4) stars more metal-rich that the sun (rSLSS objects).

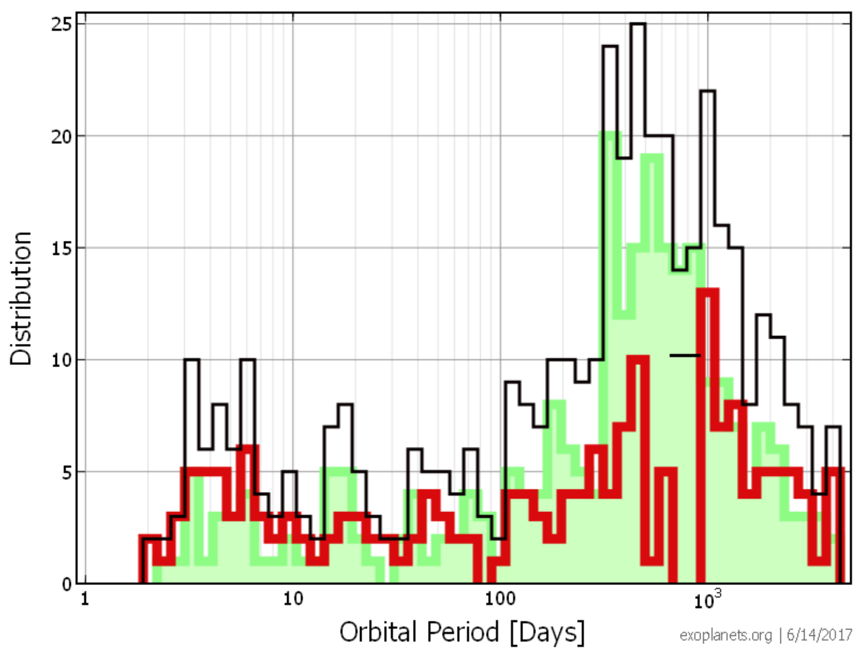

Figure 1 The width of the deep gap in log period space is shown as a line (above the line of 10 counts delineating periods from 653.2 to 923.8 days) in the number distribution of counts by period of all 435 planets (block) found by radial velocity (RV, "objects") by the end of 2016, with periods up to 5000 days, beyond which the observations fall off. The binsize is set to best show the shallow gap. We show below this (red) the 243 ``SLSS'' objects selected for having stellar parameters more like the sun in effective temperature, surface gravity, and not having a stellar companion. Two bins have zero objects, an unexpected result. We show the difference between the full and SLSS distribution in green, which shows no sign of a gap. In the full distribution, it appears that there is a single ``1 AU'' or ``short period'' pileup at periods from 100 to 1000 days. Though the double peak bracketing a gap pattern is visible here, it looks like random jitter rather than the strong feature that it is when a more focused sample is chosen.

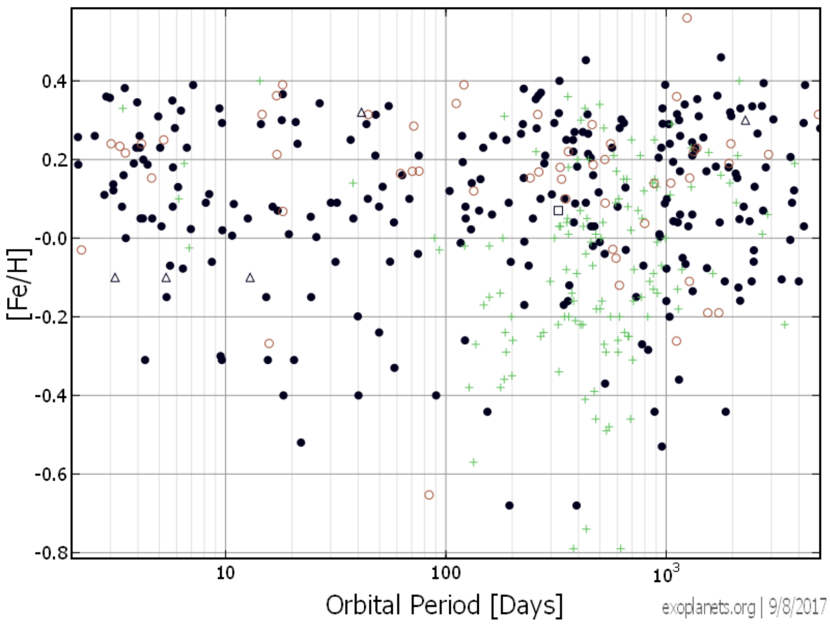

Figure 2 Objects plotted by [Fe/H]* versus period shows that a gap in the SLSS objects (filled black circles), above a boundary that is a little below zero (solar) in metallicity, [Fe/H]*. There is no gap, however, in SLSS objects below an [Fe/H]* of -0.07. There is no such gap the LSG objects (green crosses). The gap is at least partially filled among the SLBS objects (unfilled red circles). Low temperature objects (triangles), and high temperature objects (squares) are too few to make a difference.

<u>Two peaks separated by a gap in the distribution of objects of metal-rich sunlike single-stars</u>: We compare the distribution by log period of the rSLSS with the distribution of the remaining and the total population in Figure 1, where we separately show the rSLSS selection from the sum of the rest of the objects, along with the grand total of all objects. We see that where the rest of the population has a single pileup, the distribution of the rSLSS objects has a gap with only six objects in the rSLSS population which separates the pileup of rSLSS objects into two peaks whose highest densities are right next to the gap. Furthermore, all six of the objects in the shallow gap are located towards the shorter period of the gap, with a domain of less than half the gap range. This leaves the longer period large half of the gap with zero objects.

We show the metallicity distribution by period in Figure 2 where we use darker symbols for the SLSS selection to show that there is a gap region for metallicities above zero with few SLSS objects on the shorter period side and zero objects on the longer period side, but with no gap in the LSG selection, and no gap in the pSLSS below a boundary that is at zero metallicity on the short period side (where the shallow part is) but the goes down to a metallicity of -0.07 on the longer period side (where the deep gap is).

These figures show that the distribution of metal-rich sunlike single-star (rSLSS) objects has significant features that differentiate the rSLSS population from the LSG and metal poor SLSS (pSLSS) population. If the boundary of rSLSS to pSLSS objects is taken to be the solar metallicity of [Fe/H]*=0, then we have 113 rSLSS objects and 41 pSLSS objects with periods from 100 to 5000 days.

The counts of the rSLSS selection are shown separately from all other objects in Figure 1. We see that the rSLSS selection has a gap while the other selections do not have any gap or show any sign of having bimodal structure anywhere in their pileups. Since the total shows the gap, the missing objects have not been observationally misidentified as being in the other selections.

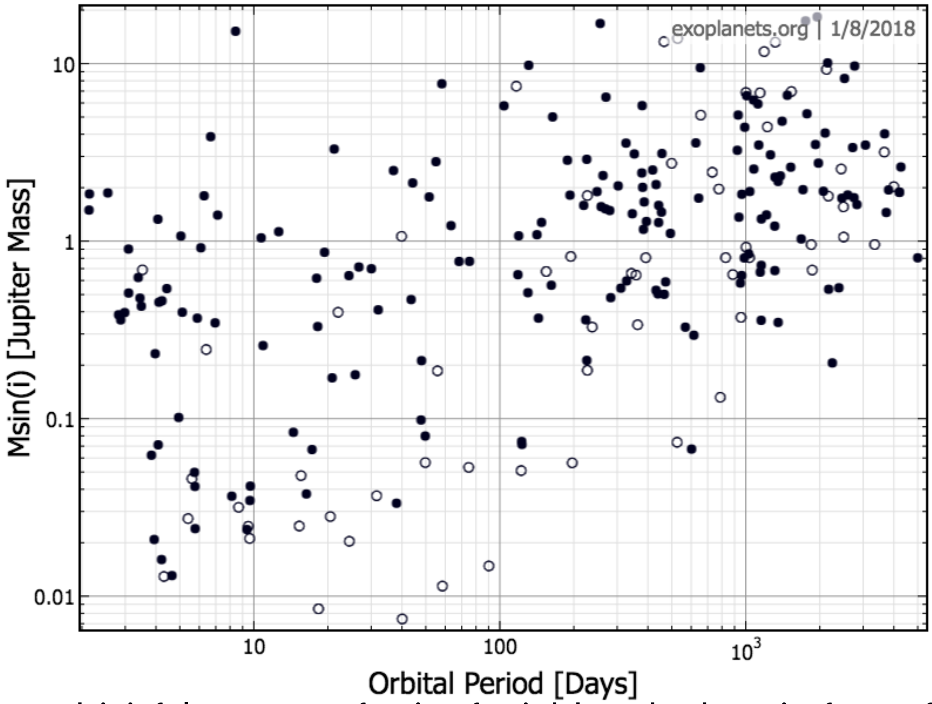

Figure 3 RV measured sin i of planet mass as a function of period shows that the gap is a feature of giant planets. We do not know if the gap extends to planets of less than 0.1 of Jupiter's mass.

<u>Gap this wide unlikely to occur by random for this many periods</u>:

We consider the likelihood of the gap either occurring by random or being an observational effect.

We consider how this gap is unlikely from two viewpoints:

1.) Considering only the rSLSS selection, we performed Monte Carlo calculations to show that an equivalent sized gap only occurs in less than one in ten thousand or more equivalent random distributions, and
2.) Considering the distributions of objects in the other selections, we find that there exists a consecutive string of 33 objects that are entirely in other selections, for which in random distributions of all selections occurs in only one in ten thousand or more distributions.

<u>Likelihood of gap randomly appearing in observations only one large part of parameter space, but not appearing at all in most other parameter spaces</u>:

It is unlikely that the deep gap would occur in the rSLSS selection of 113 of the 313 total objects with periods past 100 days, 36% of the exoplanet population in the main region, but not occur in the remaining 60%. In the region of periods from 653.2 to 923.8 days where there are zero rSLSS objects, this means that the 33 other objects appear in a consecutive series of not having any rSLSS objects.

We calculate that when there should be a 36% chance of having an rSLSS object, it is extremely unlikely to have 33 objects in a row that are not an rSLSS object.

We describe in Methods how we calculate the likelihood of having 33 objects anywhere within a set of 313 randomly being all of one type to be

$$280(1 - 113/313)^{33}=1.1 \times 10^{-4},$$

which is less than one *<u>distribution in 9000.</u>*

Conclusion of Topic 1:
We conclude that this gap feature is most likely physical, so it should be considered when discussing the number of planets in the habitable zone.

References:

Han, E. Wang, S.X. Wright, J.T. Feng, Y.K. Zhao, M. Fakhouri, O. Brown, J.I., and Hancock, C., 2014, Exoplanet Orbit Database. II. Updates to Exoplanets.org, PASP, 126,827.

Taylor, S.F., **T13a**, 2013, Iron abundance correlations and an occurrence distribution discrepancy from ongoing planet migration, arXiv:astro-ph/1305.5197.

Taylor, S.F., **T13a**, 2013, preface titled, “Seeking Support For My “Campaign For Participation”, prepended to white paper, “Hot Big Planets Kepler Survey: Measuring the Repopulation Rate of the Shortest-Period Planets”, arXiv.oastro-ph/1309.3283 .

Appendix: How to obtain a histogram showing the gap :
Go to http://exoplanets.org/plots and choose an advanced histogram. Choose to histogram the period (per), and click log scale.
Then enter this filter:
MSINI[mjupiter] > 0.0 && FE > 0.00 && PER[day] > 1 && PER[day] < 5001 && STARDISCMETH = 'RV' && TEFF[k] > 4500 && TEFF[k] < 6500 && LOGG > 4.00 && ! BINARY && ECC < 01.20 && DATE < 2016
Adjusting the bins:
Setting #bins in the "Configure Histogram" choice at 27 bins with a minimum of 1.02 works and max of 4.34e+3 works well at showing the two peaks and most of the gap. The important thing is to get a bin boundary below the period of 923.8, and the "deep" (zero objects) gap goes down to 653.22 days. From there to the boundary of the short period pileup at 493.7 days, there are six objects in what we call the "shallow" gap. Then the gap from Figure 1 pops right out!

Topic 2: Including marginalized demographics in participation in all sciences:
In response to encouragement to making the case for enabling greater demographic participation, we note the role that bullying has harmed this discovery being disseminated throughout the astronomy community to make the point that it is essential that consideration be given how to better enable those scientists who have been marginalized by any kind of harassment including bullying to remain active without being forced to not participate sufficiently to retain a reasonable chance of remaining employed in science.

We use how this discovery was first publicly posted in 2013, yet due to the author’s challenged situation, this discovery has only finally been submitted for publication in late 2017. It has been simply too challenging for the author to complete a readable version of the paper when deprived of support and of deprived of being in an environment in which he could discuss write-ups with colleagues, all the while having an untreated learning disability aggravated by the trauma of being bullied.

We promote the adoption of a simple ethical practice that peer review include the requirement that no significant author be intentionally ostracized off a paper. Paper writing collaborations must as a matter of standard policy respond to any complaints that co-authors are ostracizing someone by inviting back in any ostracized should-be author. The author group should require that co-authors not exclude someone from sharing data that the ostracized person contributed to obtaining, by enabling the target to follow the “go around the observatory” practice advocated in the preface attached to the white paper of Taylor (2013b).

“Pale Orange Dot”: Titan as an analog for Early Earth and Hazy Exoplanets

8 January 2018

Independent Contribution to Astrobiology Science Strategy for the Search for Life in the Universe

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Introduction

Before Earth became a “pale blue dot”, it may have been a “pale orange dot”. Indeed, Titan has long been of interest as a possible “frozen early Earth” – a prebiotic environment, with similarities to an inferred Archean Earth (3.8–2.5 billion years ago), and a possible window into our planet’s ancient origins. Photolysis-driven reactions within its thick, nitrogen-methane atmosphere lead to the generation of > 10,000 tons of organic solids each year in the form of haze particulates [1]. On Titan, the products of methane photolysis create a thick global haze layer, eventually depositing on Titan’s surface. This robust engine of organic synthesis represents one hypothesized analog for the pre-oxic Earth, in which endogenous atmospheric chemistry leads to the generation of prebiotic molecules that triggered the origin, or supported the evolution, of life on our planet [2]. Yet early Earth is not the only planet for which a period of organic haze formation may provide clues into the formation and evolution of life: extrasolar planets with observable Titan-like hazes provide a new frontier in the search for evidence of life in the universe. Because the hazes on rocky planets can be generated by biogenic methane, they can even be biosignatures [3]. Titan provides a natural laboratory for understanding the connection between haze formation and the planetary environment on a world lacking abundant, observable life, providing necessary context for interpretation of biological versus non-biological organic hazes waiting to be discovered elsewhere.

The aspects by which Titan serves as our best analog for early Earth and hazy exoplanets are intricately linked, and require further exploration of Titan to advance our understanding of both of these types of worlds. The former was discussed in the last Decadal Survey [4]; the latter has come to more significant appreciation in the last few years as the discovery, characterization, and known distribution of exoplanet typologies has expanded exponentially. In this white paper, we discuss how the unique aspects of Titan provide us with a singular destination that can shed light on the critical processes at play on habitable worlds throughout the universe [5].

Titan as a model for Early Earth

The timing and mechanism for the emergence of life on Earth is still unknown, as are the geological and environmental conditions that fostered its origin. Mildly reducing atmospheres are favorable for the synthesis of organic compounds as well as the resolution of the Faint Young Sun Paradox [6-8]. Given evidence that the upper mantle was at or near the present redox state [9], carbon dioxide may have been the primary carbon source product in the primitive atmosphere. Recent modeling has shown that moderate amounts of greenhouse gases (CO_2, CH_4) could provide sufficient warming for oceans on at least part of the planet [10]. Laboratory experiments indicate that organic synthesis can proceed even with low ratios of CH_4/CO_2 [11, 12] and possibly with enhanced H_2 from reduced escape rates [13, 14]. With a sufficient source of abiotic CH_4, either from impacts or serpentinization [15-17], it’s possible that global atmospheric synthesis could have provided the necessary ingredients to aid in the origin of biochemical systems [18, 19]. It can be challenging to substantiate an abiotic flux to achieve the ~100-1000 ppmv levels needed for haze formation in the presence of abundant CO_2. Terrestrial CH_4 fluxes on this order are provided by the biosphere, which has led to skepticism that the prebiotic planet could have maintained such levels. Alternatively, atmospheric synthesis supported by a flux of CH_4 from methanogenesis in the pre-oxic environment after the origin of life [20] may have delivered an important source of food or ultraviolet shielding to the burgeoning biosphere [21]. Thus, such a haze layer may have played a critical role in the shaping of our habitable planet, yet its formation, chemical, and optical properties are still not properly understood.

The presence of a haze layer on early Earth formed from photolysis of CH_4 is intriguing, with implications for climate feedbacks and endogenous production of organics on the young planet. Given recent evidence that the Earth experienced several intervals when a transient organic haze globally veiled our planet [22-25], this haze would have dramatically altered our planet's climate, spectral appearance, and photochemistry [22, 26-33]. **Titan is our best analog for this process – regardless of the source of the CH_4 on Archean Earth – and provides a window into key processes on early Earth or exoplanets that are otherwise inaccessible.**

Given our understanding of the requirements for life as we know it, the provision of organic material is critical for habitability. A global haze layer on early Earth, if similar to that observed on Titan, could rival or surpass the delivery of exogenous organic material [12]. However, the production rates depend on a detailed understanding of the chemical haze formation mechanisms in the upper atmosphere, and how the process on the early Earth would compare or contrast to that actively operating on Titan. The Cassini/Huygens mission greatly improved our understanding of this process at Titan, and laboratory studies have shed light on the driving chemical reactions on Titan and possibly on early Earth. Yet there are still numerous unknowns regarding the chemical mechanisms of haze formation at Titan which also limits our understanding of its relevance for Earth. Some of these open questions include: (1) the composition and formation mechanisms of heavy ions in the ionosphere, and how critical these are for the generation of the haze material; (2) the relative influence of oxygen-containing species on the composition and optical properties of the haze material and the possible production of prebiotic molecules; (3) what is the age, source(s), and sink(s) of CH_4 on Titan, with implications for the timeline of CH_4 photolysis and extent that organic haze formation has shaped the environment; (4) the relative importance of different energy inputs at Titan for the production and properties of the haze; and (5) the extent of chemical processing as the upper altitude material descends through the atmosphere, prior to interacting with the surface [see full discussion in 34].

The photochemistry that initiates haze formation may have provided a mechanism for large-scale nitrogen fixation [35, 36], a means for the inclusion of nitrogen in any proto-biosynthesis that pre-dates or supports the evolution of critical biological nitrogen fixation [37]. Extreme UV photons dissociate N_2 on Titan, and the flux of such photons would be greater on the early Earth, given the closer location and shift to shorter wavelengths even with the lower overall luminosity [38]. Cassini measurements have underscored the important role of nitrogen in the formation of organic molecules [39], and comparable chemistry in the upper atmosphere of early Earth may play a similar role in providing a source of activated nitrogen to the surface environment [40]. Improved understanding of the role of ion chemistry on the inclusion of nitrogen and the composition of hazes is needed to evaluate potential for this to serve as a nitrogen cycle on early Earth.

It is clear that Earth's early atmosphere may have been an important source of prebiotic molecules to the surface environment, to either participate in prebiotic chemistry or to support an existing biosphere. Even in Titan's reducing atmosphere, photochemical models show that a full coupling between hydrocarbon, oxygen and nitrogen chemistries occurs and impacts organic haze properties [41]. Given its thick, organic-rich atmosphere, the extent of prebiotic chemistry on Titan can only be assessed through in situ exploration of the atmosphere and at the surface. Whether or not there is evidence of life discovered on Titan, the global production of haze materials and abundant deposited surface products could serve as a critical benchmark of the extent of abiotically synthesized complex organic chemistry. Through comparison against such an example we can better recognize whether the differing conditions on early Earth are sufficient to produce atmospheric synthesis that can promote or respond to a biosphere.

Finally, a haze layer on the early Earth would cause climate effects that impact the habitability of the planet [22, 26, 28-30, 42]. Again, Titan is the only rocky body where we can study the planet-wide effects and feedbacks of haze to understand the complicated interplay between upper atmosphere chemistry and the resulting climate and spectrum of light at the surface. For one, the anti-greenhouse effects of Titan's haze layer – scattering and absorbing incoming solar radiation, heating the stratosphere while cooling the planet's surface [43] – is dependent on the chemical composition and optical properties of the haze material as well as the incident radiation [42]. Cooling and radiative shielding is highly sensitive to the specific chemical and microphysical growth mechanisms, as well as production feedbacks related to the amount of CH_4 present [30]. Such feedbacks may also be critical for evaluating whether haze itself is a biosignature [3].

Titan as a model for Hazy Exoplanets

Organic hazes are critically important to consider when observing and understanding exoplanet environments for four main reasons: (1) Photochemical hazes are ubiquitous in solar system atmospheres; (2) they strongly impact planetary climate and overall energy balance; (3) they can frustrate attempts to remotely probe deep atmospheres because (4) they strongly affect the appearance of a planet's spectrum. In the near future, the James Webb Space Telescope (JWST) will be capable of observing planets in transit transmission. Beyond this, large space- and ground-based telescopes in coming decades may allow direct imaging of a larger sample of potentially habitable worlds, enabling the search for biosignatures in reflected light spectra [44-48].

Several known large (i.e. gaseous) exoplanets exhibit signs of hazy atmospheres [49-53], possibly due to organic hazes [e.g., 54]. The ubiquity of hazes in the solar system, and the long anoxic history of our early planet suggests we should anticipate haze-rich Earth-sized worlds when characterization of Earth-sized exoplanets in the habitable zones of distant stars becomes possible [55]. Exoplanet spectra are strongly affected by hazes: even hazes that are optically thin all the way down to the surface in reflected light can become optically thick at higher altitudes in transit transmission observations due to the longer path lengths inherent in these types of observations. This can make it challenging to observe gases or clouds deeper down in the planetary atmosphere. Titan's unique position in the solar system as a nitrogen-dominated rocky world with a thick haze has already led observers to consider it in the context of transit transmission observations of hazy exoplanet atmospheres [56]. In reflected light, hazes can also dramatically shape the remote observable properties of planets.

Organic haze formation, as a photochemical process, is also significantly affected by the UV spectrum of the host star [31]. The CH_4/CO_2 ratio resulting in the most efficient haze formation in the atmosphere of a hazy early Earthlike exoplanet may be strongly affected by the stellar properties, but a more complete understanding of the role of oxygen-bearing gases on haze formation chemistry is required to fully understand how organic haze formation efficiency varies in different stellar environments.

Haze formation on early Earth may have been driven by biologically-produced methane. In fact, high methane fluxes consistent with biology may be required to explain haze formation on planets with Earth-like CO_2 levels [3]. Therefore, in some contexts, organic hazes may be spectral biosignatures. Hazes may also feedback effects on the biospheres that generate them, through their cooling effects and their UV shielding properties that may variously help or hinder biological processes. Organic hazes may play a critical role in our understanding of the habitability of anoxic exoplanets in the habitable zones of their stars.

A more detailed understanding of the processes that form hazes in Titan's atmosphere is needed to better model hazes in exoplanet atmospheres to predict which types of planets are more likely to host hazy atmospheres. Additionally, better understanding of the optical properties of Titan-like hazes is needed to anticipate the spectral observables, UV shielding, and climate feedbacks of hazes on habitable worlds. In our solar system, Titan serves as an important counterpoint to the potential for organic haze to be a biosignature in some types of atmospheres. A thorough understanding of haze formation in an abiotic environment is needed to understand how to distinguish biologically-mediated haze formation from purely abiotic processes.

Next steps for Titan

A top-to-bottom in situ investigation of Titan's organic chemistry and haze formation from the atmosphere to the surface is needed in order to fully understand the generation of its organic material and draw comparisons with other bodies of astrobiological interest. Orbital platforms with the capability to measure ions and neutrals up to high masses (>> 100 amu) would allow us to understand driving chemical formation mechanisms. Middle and lower atmosphere compositional measurements of haze particles and clouds, using aerosol measurement technology commonly used to study the Earth's atmosphere, would provide the key link between formation, processing, and the eventual depositional products. Surface measurements that understand the diversity of processed materials, including those potentially exposed to transient water [57], or search for signs of 'exotic' biochemistries. (See companion white papers, "Seeking the origins of aqueous life on Titan", Cable et al. and "Seeking non-aqueous life", Malaska et al.)

Continued laboratory studies and simulations are needed that probe the chemical formation mechanisms of Titan haze with a fidelity that allows for the extrapolation to other chemical systems, such as Earth- or exoplanet-like gases. Improved data for photochemical and climate models will enhance our ability to predict which environments could support an organic haze and what the properties might be. This will be invaluable in the reverse interpretation of exoplanet atmospheres from observation.

Conclusion

Exploration of Titan and dedicated observation and measurement of its organic cycle is needed to give us a singular data point regarding the extent and efficacy of global organic synthesis and prebiotic chemistry. Such efforts vastly increase our ability to recognize other habitable worlds, to understand whether haze itself could be a biosignature, and to better understand critical conditions on the early Earth at the time of the emergence of life.

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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

Response to A Call for White Papers
"Astrobiology Science Strategy for the Search for Life in the Universe"

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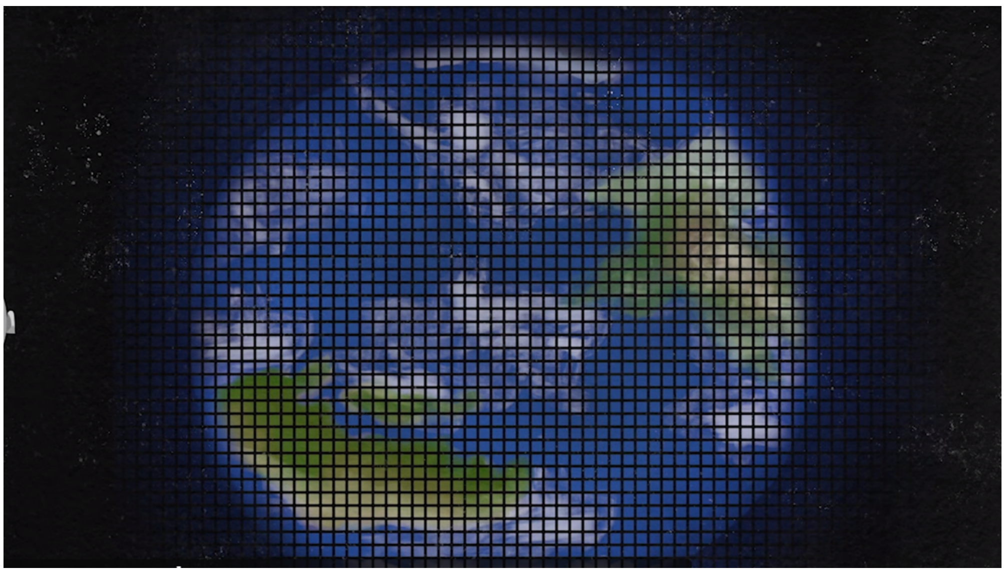

A 1-meter telescope with a coronagraph (with 10^{-6} suppression) placed in the focal area of the solar gravitational lens (SGL) can image an exoplanet at the distance up to 100 light years with a kilometer-scale resolution on its surface. In addition, spectroscopic broadband signal-to-noise ratio is ~10^6 in 2 weeks of integration time, providing this instrument with incredible remote-sensing capabilities. See concept description at https://www.youtube.com/watch?v=Hjaj-Ig9jBs

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December 2017

A Mission to Find and Study Life on an Exoplanet

A White Paper for the NAS Space Science Board

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Finding life on another world is perhaps the principal goal of space exploration, both for the public funding such exploration and for the scientists seeking to understand the questions of life in the Universe. Numerous apparently habitable worlds, potential abodes of life, have now been discovered around other stars, and many more can be expected to be discovered in the next few years. It is almost certain that a tantalizing hint of life on one or more worlds will be obtained. But, only a hint – to determine life will require either going to those other worlds or remotely studying them in detail over a long period of time. Both are beyond our present capability.

Going there (perhaps tens of light-years from Earth) will remain impossible, if not forever, certainly for a long time. Detailed remote study is only possible with very large telescopes, tens of kilometers, at very high cost, or by using the very high magnification and angular resolution provided to us by nature – the solar gravity lens (SGL). The SGL results from the natural phenomenon of the large gravitational field of the Sun to 'bend' and focus light from a distant object, e.g. an exoplanet. The focus is a line – along which a spacecraft could fly for years to make repeated high-resolution observations. In the foreseeable future, a small-sized telescope (1-2 m) could operate on the focal line of the SGL at distances between 600 – 900 AU from the Sun, to provide kilometer (km) scale direct images of a distant exoplanet. This instrument could deliver ($10^3\times10^3$)-pixel images of "Earth 2.0" at distances of up to 100 light years (ly) and with a spatial resolution of ~10 km on its surface, enough to see its surface features with signatures of life.

According to Einstein's general relativity, gravity imparts refractive properties on space-time causing a massive object to act as a lens by bending photon trajectories. As a result, for a given solar impact parameter, the gravitationally deflected rays of light passing from all sides of the lensing mass converge at a focus, as shown in Fig. 1. Gravitational lensing is a well-known effect and has been observed over cosmological distances where relatively nearby galaxies, or even clusters of galaxies, act as gravitational lenses for background galaxies, and even in our Galaxy where micro-lensing of stars in the Galactic bulge or in the Magellanic clouds are caused by intervening (sub-)stellar bodies. In our Solar System, this effect was originally observed by Eddington in 1919 (thus confirming formally Einstein's theory) and now is routinely accounted for in astronomical observations and deep space navigation (Turyshev 2008).

Of the solar system bodies, only the Sun is massive enough that the focus of its gravitational deflection is within a range of a realistic mission. Depending on the impact parameter, the focus of the SGL is a semi-infinite line that begins at ~547AU. The "focal line" (FL) of the SGL is broadly defined as the area beyond 547AU from the Sun on the line that connects the center of an exoplanet and the center of the Sun. By naturally focusing light from a distant source (Eshleman 1979; Turyshev & Andersson 2003), the SGL provides brightness amplification (~10^{11} at λ=1 μm) and extreme angular resolution (~10^{-10} arcsec) in a narrow FOV (Turyshev 2017; Turyshev & Toth, 2017). The entire image of an exoplanet at 100 ly away from us is compressed by the Lens into a small region with diameter of ~1.3 km in the immediate vicinity of the focal line. In the pencil-sharp region along the focal line, the amplification and angular resolution of the SGL stay nearly constant well beyond 2,500 AU. For example, to appreciate the enormity of the magnifying power and resolution of such a system, a 1-m telescope placed on the FL of the SGL at 750 AU from the Sun has a collecting area equivalent to a telescope with diameter of ~80 km and angular resolution of an optical interferometer with a baseline of 16 Earth's radii. Such a telescope at the focal region of the SGL would provide high-resolution images and spectroscopy of a habitable exoplanet.

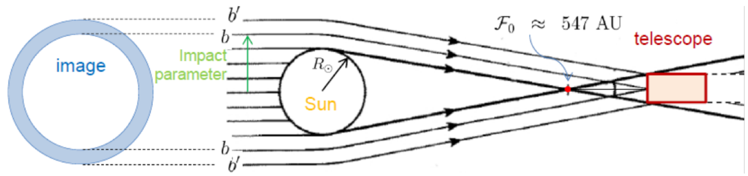

Fig. 1. Imaging of an exo-Earth with solar gravitational Lens. The exo-Earth occupies (1km×1km) area at the image plane. Using a 1m telescope as a 1 pixel detector provides a (1000×1000) pixel image.

As seen from a telescope at the FL, the light from an exoplanet occupies an annulus surrounding the edge of the Sun (Fig. 1). This light, while magnified greatly, is still much dimmer than the Sun. A modest coronagraph (~10^6 suppression) would be used to block the solar corona, so that the exoplanet's light could be detected at the telescope.

At 550 AU the Sun subtends ~3.5''; for λ=1 μm, the diffraction limited size of a 1-m telescope has a beam size of ~0.1" (or 35 times smaller; thus, no need to go beyond 1,000 AU). Majority of light in this narrow annulus comes from a ~(10 km × 10 km) spot on the exoplanet's surface. However, light outside the annulus would come from the adjacent areas on the exoplanet. This light will also be blocked by the coronagraph.

The instrument for a mission to the focal region of the SGL should implement a miniature diffraction-limited high-resolution spectrograph, enabling Doppler imaging techniques, taking full advantage of the SGL amplification and differential motions (e.g. exo-Earth rotation). Taking into account the solar corona the broadband SNR is ~10^3 in 1 sec. Thus, if we want to get SNR of 10^6, we would need 10^6 seconds (or ~2weeks). This implies that for a spectral resolution of 10^4 the SNR (in each spectral element) would be 10^4. With spectral resolution of 1 million, we would still have SNR = 10^3, again in only 2 weeks of integration. Clearly shown a significant potential for finding and studying life on an exoplanet by remote sensing its atmosphere. A coronagraph capable to satisfy the requirements for imaging with the SGL was recently designed at JPL (Shao et al. 2017). This design is able to achieve the solar light suppression of better than 10^{-7}, providing a healthy margin for the mission development. Given the rapid development of coronagraphic capabilities, we can therefore assume that direct imaging will provide spectro-photometric characterization of the exo-Earth.

Fig. 2. An image of the Earth with resolution of (10^3×10^3) pixels. To illustrate imaging capabilities of the SGL.

The image of the exo-Earth at ~100 ly would extend ~1.3 km at the location of the spacecraft on the optical axis of the SGL. The spacecraft would have to scan this (1.3 km × 1.3 km) area one pixel at a time (or consist of a constellation of several apertures) to develop a multi-pixel image of an exo-Earth with resolution of (10^3 × 10^3) pixels as shown in Fig. 2. A computer animation of a mission concept to capture images and spectroscopy of the exoplanet through the SGL was recently developed and is available on YouTube (DeLuca 2017).

Effects of the radial/azimuthal plasma density of the solar corona (Turyshev & Andersson 2003, Turyshev & Toth 2017, op.cit.) on the structure of lensing caustic were recently taken into account, including analysis of the contributions for the solar gravitational harmonics, second order effects, and chromatic structure of the caustic (Turyshev & Toth 2018). These effects result in additional aberrations that modify the caustic formed by the Sun which may be quite useful in the image reconstruction process. The additional aberrations (from higher-order gravitational harmonics of the Sun) are well-known and are easy to account during deconvolution. In fact, they provide some variability in the image that may be used to our advantage in the image reconstruction, perhaps, leading to even a higher precision of reconstructed images.

While all currently envisioned NASA exoplanetary concepts aim at getting just a single pixel to study an exoplanet, a mission to the SGL opens up a breathtaking possibility for *direct* ($10^3 \times 10^3$) pixels imaging and spectroscopy of an Earth-like planet up to 100 ly with resolution of ~10 km on its surface, enough to see its surface features and signs of habitability. Such a possibility is truly unique and was never studied before in the context of a realistic mission.

The key new technologies that now enable consideration of such a mission are smallsats (spacecraft less than 100 kg with power, communications, precision control and navigation, etc.) and solar sails. One interplanetary sail has already flown to vicinity of Venus (JAXA's IKAROS) (van der Ha et. al., 2015) and another to a Near-Earth Asteroid is now being developed by NASA (NEA Scout) (McNutt et. al., 2014). While conventional propulsion (chemical) in principle could be used with a large solid rocket motor flying very close to the Sun, even with optimistic assumptions the speed of such a probe is limited to about 17 AU per year (Stone, Alkalai & Friedman, 2015). As described below a (300 x 300) meter solar sail, with a spacecraft mass of 100 kg could fly out of the solar system at ~25 AU per year, enabling reaching the SGL in a less than 25 years of flight.

Friedman & Garber (2014) first considered the SGLF as an interstellar precursor. They studied solar sail requirements to reach exit velocity speeds of over 20 AU per year. The results are summarized in Fig. 3. Garber (2017) has extended this analysis to consider the area/mass requirements to reach an exit velocity of up to 40 AU/year. His result is given in Fig. 4. Sail area to spacecraft mass ratios of 900 m^2/kg yield a speed of 25 AU/year, 30 AU/year requires A/m=1400 and 40 AU/year requires A/m= 2550.

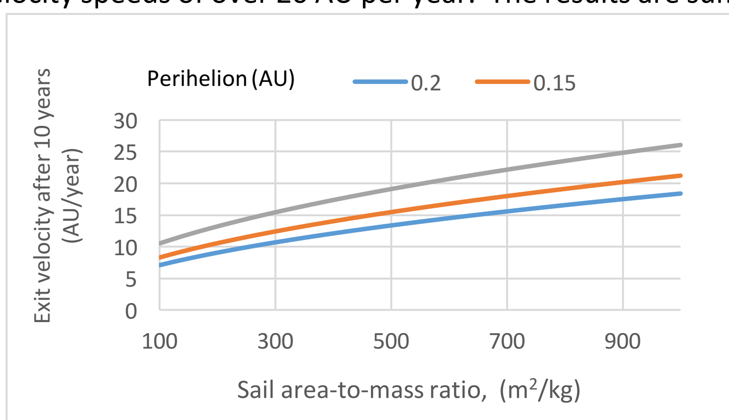

Figure 3: A solar sail spacecraft exit velocity from the solar system vs. sail area to spacecraft mass ratio and perihelion distance.

Since any spacecraft will need power – presumably a small radioisotope generator, we consider that radioisotope electric power (REP) thrusters can provide an additional boost to the solar sail spacecraft as well as propulsion for in-space maneuvers, such as midcourse navigation and maneuvers in the Einstein Ring to collect the image pixels. A JPL study (Liewer et al. 2000; Mewaldt & Liewer 2000) cited an Advanced Radioisotope Power System delivering 106 W weighing 8.5 kg (~12.5 W/kg). A system this small would be insufficient for boosting spacecraft velocity but might provide enough propulsion for small maneuvers and attitude control. Quantitative studies need to be done in a system design. The REP might boost the velocity by as much as 20%, e.g. 5 AU/year -- albeit, likely with a heavier system.

When we reach the focus of the SGL, we must continue to fly along the focal line for a flight time as long as it took us to get there, e.g. another 25 years. Images of the exo-planet will have to be constructed through a complicated de-convolution process of pixels sampled in the Einstein ring around the FL (see Fig.1). That is the spacecraft will have to sample the image of an exo-Earth with the diameter of 1.3 km around the FL while travelling at speeds ~25 AU/year. Tethering or electric propulsion could be used to perform raster-scanning with a spacecraft located >550 AU away. For an exo-Earth 100 ly away, the planet's image moves in a 45,000-km diameter 1-year orbit. Its image at the focus of the SGL is ~1.3 km in diameter. One way to scan the image of an exo-Earth is to conduct a spiral scan to follow the planetary motion while using a ~1.3-km tether and the RTG on the other end of it (to balance the spacecraft). This reduces the fuel requirement for raster scanning the image.

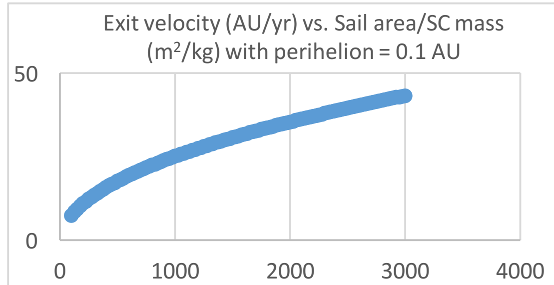

Figure 4 Exit velocity as a function of sail area/mass ratio.

Conclusion

Ever since Galileo invented a telescope, astronomical telescope making has been an evolving discipline. The task of designing of a modern telescope is complex, involving consideration of materials, detectors, precision manufacturing, tools for optical and thermal analysis, and etc. The largest telescope so far is the European Extremely Large Telescope (ELT) with aperture of 39.3 m that is currently under construction in Chile. A telescope with diameter of tens of kilometers in space to get a megapixel scale direct image of an alien world is beyond our technological reach. The SGL holds the promises of providing us with such cosmic capabilities.

It remains to be determined just how complex will be the capturing and creation of direct images of an exo-planet using the SGL. It also remains to be determined what would be the cost of a mission to its focal region. However, if it does prove to be a feasible mission, there may be cost and science tradeoff between remote sensing using the solar gravity lens and flying to, operating and returning data from a planet in another star system many light years away. In any case, the first job is to simulate creating the image in the SGLF. This is being done in a current NIAC study (Turyshev et al., 2017). Although we investigate the question of spacecraft design of how to reach the extremely large regions outside the solar system, the primary emphasis is placed on the feasibility of mission operations in support of the primary science objectives – the high-resolution imaging and spectroscopy.

The SGL offers a unique means for imaging exo-planets and determining their habitability. A complete set of requirements to use it to create such an image remain to be determined. A comprehensive study of a Solar Gravity Lens Focus mission is needed. Theoretical considerations are promising, both for getting there and for capturing high resolution images and spectra of potentially habitable exo-planet. The mission has the potential of being the most (and perhaps only) practical and cost-effective way of obtaining kilometer scale resolution of a habitable exoplanet, discovering, and studying life on other worlds.

Concluding, we suggest that it is time to initiate a study of a mission to the deep regions outside the solar system that will exploit the remarkable optical properties of the SGL to effectively build an astronomical telescope capable of direct megapixel high-resolution imaging and spectroscopy of a potentially habitable exoplanet. Although theoretically seem feasible, the engineering aspects of building such an astronomical telescope on the large scales involved were not addressed before. There are many unique and exciting features of such a mission to the SGL that warrant such a study in the near time, perhaps even at the beginning of the next decade.

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Cover page

Title: **Terrestrial Hot Springs and the Origin of Life: Implications for the Search for Life Beyond Earth**

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Terrestrial Hot Springs and the Origin of Life

Significant new chemical, geological, and computational evidence increasingly supports the hypothesis that life originated in hot spring fields _on land_, rather than at deep-sea hydrothermal vents. This has profound implications for Astrobiology and the search for life beyond Earth, not only for site selection *on* a planet, but also which of the planetary bodies to investigate.

An origin of life on land is supported by the following:

1) Surface pools would have been able to concentrate in-fall from meteoritic sources and interplanetary dust particles, which were many times more voluminous during earliest Earth history[1] and contain abundant key building blocks for life including fatty acids, nucleobases, and amino acids[2-4].

2) Terrestrial hot springs have the capacity to undergo wet-dry cycling – in some cases many times per day (e.g., Yellowstone's Old Faithful) – both at pool margins on the surface and in fractures in the near subsurface where prebiotic reactions would be shielded from harsh UV radiation. Wet-dry cycling has been shown to be critical in overcoming 'The Water Problem', whereby most of the important prebiotic organic reactions require a form of dehydration (condensation reactions, in which water is a leaving group) to form long-chain organic polymers (e.g., polysaccharides, oligonucleotides, and polypeptides) from their simple building blocks (e.g., amino acids)[5-7]. In fact, without continual re-synthesis, polymers break down in the presence of water and polymerization cannot occur without the support of activating metabolic reactions[8], presenting a potentially insurmountable barrier to a deep-sea vent Origin of Life (OoL) scenario[9].

3) Hot spring pools contain a mixture of meteoric water and condensates of magmatic vapors, producing a range in temperatures and pH, including acidic pools that have been shown in the laboratory and at field sites to support the formation of membranous compartments (or protocells: Fig. 1)[10-13]. Such protocells are able to encapsulate organic polymers and subject them to combinatorial selection through wetting-drying cycles that drive ever-increasing complexity and emergence of biological functions[14,15]. Freshwater is important because microorganisms from all three branches of life contain an internal cytoplasm with K^+/Na^+ ratios very different from seawater, or the possible compositions of ancient seawater, but similar to freshwater; indeed, it has been shown that saltwater presents a barrier to the formation of membranous compartments[16].

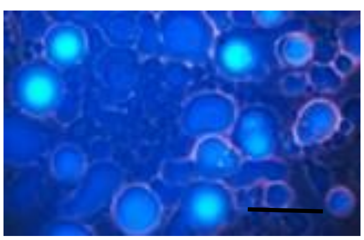

Fig. 1: Image of a lipid-mononucleotide mixture stained with a dye that strongly interacts with nucleic acids, which is concentrated in some (but not all) of the vesicles after being put through four wet-dry cycles, forming protocells. Scale bar is 10 µm. Image from D. Deamer.

4) Hot spring pools can, and do, concentrate a variety of prebiotically important elements, including not only H, N, O, P, and C, but also Fe, S, and P, as well as B, Zn, and Mn[17,18] (e.g., the Fe-rich Chocolate Pots spring in Yellowstone[19]; boratic sinters in India[20]).

5) Hydrothermal fields on land receive energy from three main sources: the hot spring system, dehydration energy, and UV light, the latter shown recently to support critical prebiotic reactions, including a pathway to activated nucleotides[21,22]. Another source is abiotic photosynthesis at ZnS and TiO_2 crystals[23], both found in an ancient Pilbara hot spring analogue site[24,25].

6) Perhaps most important for an OoL scenario is the extreme complexity of terrestrial hydrothermal fields that can consist of a hundred or more pools ranging from acidic, through neutral, to highly alkaline, which are hosted by a variety of mineral surfaces, and each of which has a different temperature and trace element concentration. In addition, pools include not only the water-rock interactions that deep-sea vents have, but also water-air/volcanic gas, and air/volcanic gas-rock interactions. Pools also have the advantage of being able to exchange contents with other pools through flows, splashing, wind, and subterranean plumbing networks that open and close on short timescales due to variable fluid/gas pressure and mineralization. This mixing of reactants, products, and energy sources results in combinations that can catalyse complex reactions creating "innovation pools" with components that become increasingly complex (Fig. 2). For example, if a component A necessary for prebiotic chemistry (such as membranes) is developed in Pool 1 and mixed with component B (polymers) produced in pool 2, then these may mix with another component to form a composite product (protocells) that emerges in the outflow channels of pool 3, and so on. Indeed, hot spring fields constitute a natural system for combinatorial, or 'messy', chemistry, supporting serial enrichment capable of creating a continuous supply of structures, building blocks, and energy sources to drive prebiotic processes through cycles of selection. Terrestrial pools are concentrating environments – through drying and evaporation – that permit many cycles of complex chemical reactions.

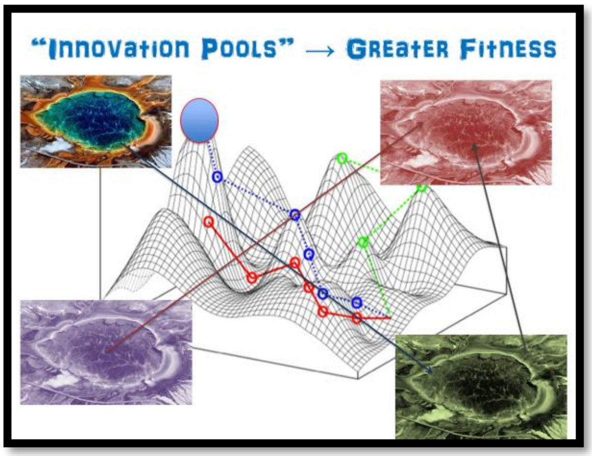

Fig. 2: Schematic diagram showing how variation and interaction among hot springs with different chemical/thermal properties (different colors) can lead to greater fitness of prebiotic molecules within innovation pools (blue ellipse). Inspired by Rachel Whitaker, U. Illinois.

7) The "sweet spot" for supramolecular (e.g., non-enzymatic RNA duplex formation[26]) assembly is ca. 10–70°C. This is because formation temperatures need to be high enough for molecules to "search" their conformation space (become distorted). Too cold and the lack of activation energy makes it doubtful that any "function" would occur between molecules – let alone generate life. Too hot and directional intermolecular forces are weakened and associations are too short for any useful chemistry to take place.

Testing of some of the above properties both in the laboratory and in the field has led to the publication of a new model for biogenesis in anoxic hydrothermal fields[13,15,17,27] (Fig. 3).

From an astrobiological perspective, the consideration of an OoL in terrestrial hot springs is important for two reasons. First, it can provide focused exploration strategies for planetary bodies where this combination of ingredients is known to have, or may have, occurred. Second, it provides us with an easily recognizable target, narrowing down the search for evidence for past life - opaline silica from hot springs is visible to orbital spectrometers[28-30] - as is the larger geographic footprint that surrounds hydrothermal alteration mineral zones[31].

Point 2 is critical because terrestrial hot spring deposits are important not only as ***hosts*** of life, but as ***preservers of biosignatures*** over billions of years[25,32-35]. Active hot springs on Earth today

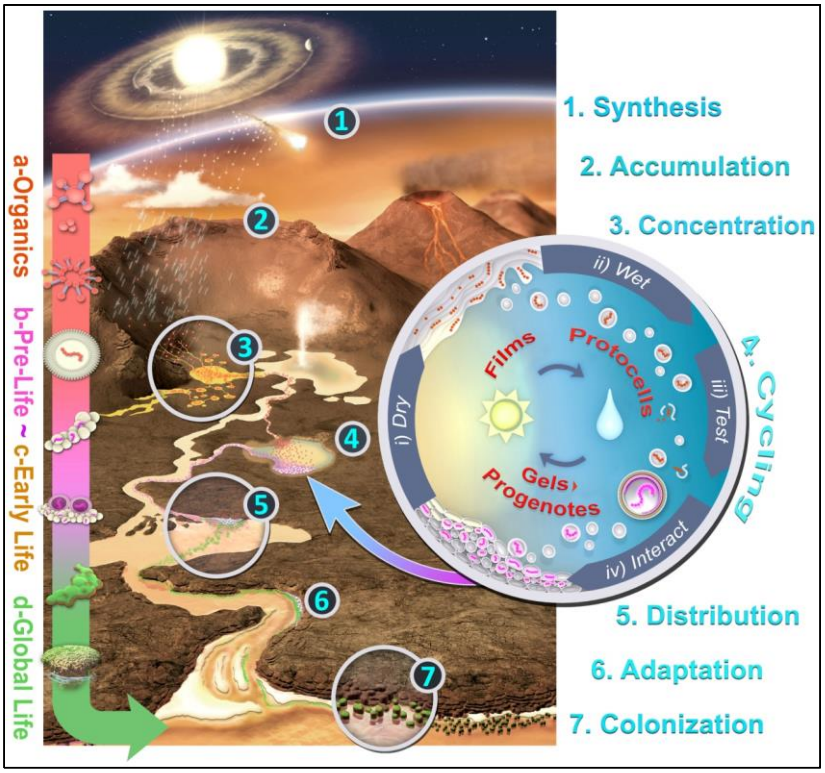

Fig. 3: The Hot Spring Hypothesis for an origin of life, illustrating how organic compounds synthesize in space (1) and accumulate (2) within interconnected hydrothermal field pools (3). These organics are then delivered to a cycling pool where protocells undergo selection toward an origin of life (4). This earliest life is then distributed along an adaptation pathway into ever more extreme environments such as lacustrine (5), salty estuarine (6), and tidal marine (7) settings[15].

are replete with life, which includes hyperthermophiles that inhabit vent areas, as well as thermophiles that occupy most of the mid-to-low temperature region of more widely distributed hot spring discharge channels and aprons upon which thick microbial mats develop[36]. Representatives of early-evolved lineages of chemosynthetic life inhabit modern hot springs and have likely done so since these lineages evolved. Moreover, the organisms that inhabit high temperature transects of hot springs (>70°C) are supported by metabolisms that are dependent on chemical energy, present prior to the emergence of photosynthesis.

Most active hot spring deposits consist of opaline silica, precipitated from dissolved silica in solution in hot spring waters through biogenic and abiogenic processes that include cooling and evaporation. Entombment of microbial mats and biofilms living on opaline silica depositional surfaces in and around hot springs results in the formation and preservation of numerous microbial biosignatures that include macro-to-microscale fabrics and structures, as well as organic and inorganic chemical traces of life[34,37] (Fig. 4). Indeed, opaline silica is the most important primary mineraloid responsible for preserving morphologically and chemically identifiable traces of life on early Earth and is the most common host lithology – by a factor of 10:1 - of the most ancient traces of life in both the Pilbara (Australia) and Kaapvaal (South Africa) cratons[38,39]. Critically,

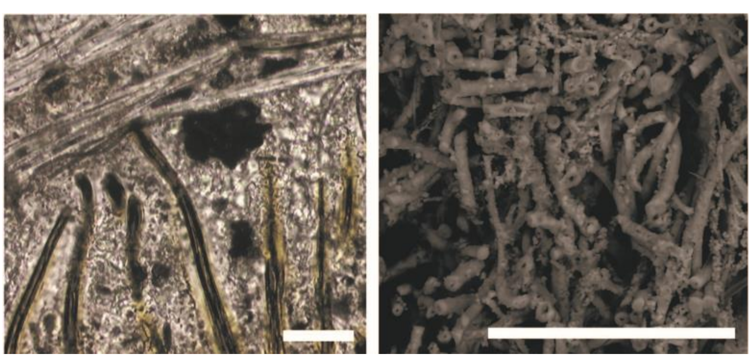

Fig. 4: Preserved microbial filaments in opaline silica sinter from El Tatio, Chile[33] (left), and Yellowstone National Park, USA (right). Scale bars are 50 µm.

it is now known that ALL hot spring deposits throughout the well-established 3.5 billion-year record of life on Earth preserve traces of ancient life[25,33,36,40,41].

Importantly, hot springs could truly be the "first and last outpost" for life on Mars, or any habitable world that becomes uninhabitable at its surface through loss of atmosphere, desiccation and irradiation. Life, if it emerged on Mars, would have had to retreat to refuges in the saline, deeper biosphere. The plumbing of a hydrothermal system could access that refuge and might carry such life with it through a temporary effusion of water up to a surface hot spring, where it may have temporary viability at this last surface outpost.

Robust evidence for hot spring deposits has already been identified on Mars by the Spirit rover adjacent to “Home Plate” in the Columbia Hills[29,30], including evidence for potential biosignatures[34]. Other candidate hot spring deposits have been observed from orbit, including one on the flanks of a volcanic cone in Nili Patera[42]. The combination of high potential for habitability and biosignature preservation of silica-depositing hot spring systems make such deposits attractive astrobiology targets for future missions to Mars, such as Mars2020.

We identify three key research areas in the study of terrestrial hydrothermal fields:

1) Combining/synthesizing data from active and ancient hot spring sites

- Continue research on active modern hot spring deposits, including distribution of textures, facies, preservation potential, types of life, etc. and develop a catalogue of active hot spring characteristics (T, pH, Eh, trace element concentrations, microbial community composition, etc.) to define habitable conditions for chemosynthetic microbial life;
- Develop a compendium of reliable biosignatures found in modern and ancient hot springs and further define life signatures within active hot springs to define where chemosynthetic microbial life signatures are best preserved;
- Investigate elemental biosignatures concentrated by microbes in modern and ancient systems to aid definitive recognition of past microbial life;
- Investigate processes and products of active mixing zones among different hot springs to define complexity, precipitation products, energetics, nature of chemical gradients, etc., and identify the processes involved in concentration of the trace elements critical for prebiotic chemistry (e.g., B, Zn, Mn, P, etc.);
- Continue studies of deep time hot spring analogues in the Pilbara and Kaapvaal cratons to better constrain early Earth conditions and preservation potential;
- Investigate silica gel as a preserving medium and source of elemental concentration.

2) Experimental work

- Investigate what happens to meteoritic in-fall in active and ancient hot springs, using laboratory simulations;
- Resolve the UV issue; conduct experiments to investigate retardation of “bad” far-UV under Hadean atmospheric conditions (CO_2, CH_4, N_2) and by silica gel (and other hot spring precipitates), vs. transmittal of beneficial near-UV that promotes reaction pathways;
- Determine more precisely what ancient (anoxic) hot spring fields were like on a planet with a high pCO_2, high temperature atmosphere that was in the early process of differentiation;
- Undertake studies exploring prebiotic chemistry in active hot springs (including surface, and near and deep subsurface) and in simulated prebiotic conditions, including wet-dry cycles,

membrane formation, organic compound concentration, supramolecular assembly, polymerization reactions and combinatorial selection of protocells;

- Examine the role of lipid membranes in organizing and concentrating monomers, promoting their polymerization and encapsulating polymer products in membranous compartments.

3) Technology development needs

- Develop and fund a sophisticated simulation anoxic chamber capable of combinatorial chemistry to discover new pathways for prebiotic chemistry. The pharmaceutical industry has utilized instruments like this for optimizing the synthesis or efficacy of new drugs with robotic devices that perform thousands of experiments in parallel. Given the complex nature of hot spring fields, a microfluidics system performing many experiments at once, with different inputs, substrates etc., and analyzing results with high throughput screening enabling closed loop operation (no manual operations), is required for OoL experiments;
- Develop high throughput methods for characterizing all other (non-single molecule) biosignatures preserved in hot springs;
- Design a biosensor for astrobiology research that can resolve and identify single molecules, based on nanopore technology.

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Geophysical Investigations of Habitability in Icy Ocean Worlds

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The interiors of icy ocean worlds hold the clues for determining their thermal and chemical make-up and thus their habitability, as discussed extensively in the Astrobiology Strategy. Here, we highlight progress since the release of the Astrobiology Strategy in demonstrating the key role of geophysical measurements for exploring the habitability of icy ocean worlds. Specifically, we focus on the unique contribution that can be made by seismology.

Ultra-sensitive seismometers, which can detect faint motions deep within the planet and activity closer to the surface, can be used to determine interior density structure while also revealing active features such as plate tectonics, volcanism, oceanic and ice flow, and geyser-like eruptions. These broad applications of planetary seismology have been well explored at solid silicate bodies, including the Moon, Mars, and Venus (e.g., Lognonné, 2005; Knapmeyer, 2009). Increasingly, investigators have examined applications of seismology ice ocean worlds in the outer solar system (Lee et al. 2003; Panning et al. 2006, 2017; Pappalardo et al. 2013; Stähler et al. 2017; Vance et al. 2017a,b). Seismology can listen for distinct "vital signs" of habitability. This includes present day activity, something no other measurement is better suited for: fluid motion in the shallow subsurface, seismic signals emanating from cryovolcanos, and internal ocean circulation, by analogy with recent developments in cryoseismology on Earth (Podolskiy and Walter 2016).

Seismology could aid in understanding the deposition of materials on the icy surfaces of ocean worlds and their exchange with the underlying oceans. While planned mapping and radar may establish the distribution of fluids and the connection of fractures to the deeper interior, only seismology can identify deeper interfaces between fluids and solids.

The large satellites, Ganymede, Callisto, and Titan, contain oceans extending hundreds of km into their interiors (Vance et al. 2014; 2017b). These deep ocean worlds are intriguing targets for astrobiology because of the possibility for remnant heat and internal activity, and also because the high pressures in their interiors may provide clues to the nature of volatile-rich exoplanets (Noack et al. 2016; Journaux et al. 2017). Fluids moving within high-pressure ices at the base of the ocean may govern heat transport through multi-phase convection (Choblet et al. 2017; Kalousova et al. 2018). Seismology is the only practical means for determining the thicknesses of these high-pressure ice layers, their temperature structure and thus their geodynamic state, and the possible presence of fluids within and between them.

Deeper seismic sources in icy ocean worlds have only been considered in the last few years. On Earth, the main source of seismic noise is the ~3-10 s background noise caused by opposing travelling ocean waves (Vance et al. 2017a). This noise source, known as ocean microseism, results from a second-order interaction between surface gravity waves. Another possible oceanic source is the low-level excitation of normal modes by motion in the ocean. Turbulent oceanic flows (e.g., in Europa; Soderlund et al. 2014) plausibly produce acoustic transmissions through the ice through dynamic pressure variations at the base of the ice shell that are comparable to those from the estimated global background noise due to fracturing at frequencies from ~10 to 100mHz (Panning et al. 2017). The possibility of a constant excitation of normal modes is intriguing, as it may shed light on both internal structure constraining the composition of the ocean (Vance et al. 2017a) and oceanic processes governing the degree of material and heat exchange (Zhu et al. 2017).

The thermal state and density of the rocky mantle indicate the nature of any continuing volcanic activity (Barr et al. 2001), water rock interaction (e.g., due to serpentinization and radiolysis), and the corresponding flux of reducing materials (H_2, CO_2, H_2S CH_4; Hand et al.

2009; Holm et al., 2015; Vance et al. 2016; Bouquet et al. 2017; Waite et al. 2017). Events in the rocky interior (and to a lesser extent events in the ice layer) will excite surface (Scholte) waves at the rock-ocean boundary (Stähler et al. 2017) that can provide information about the properties of the seafloor. Hydrothermal activity could generate seismoacoustic signals that travel through the internal ocean and ice where they could be intercepted by a surface seismometer.

Science Goal	Science Objectives	Rationale / Relevance to Habitability	Scientific Measurement Requirements	
			Observables	**Physical Parameters & *Derived Properties***
Determine Europa's habitability, including the context for any signatures of extant life	Characterize the [global/local] thickness, heterogeneity, and dynamics of the ice	Efficiency of redox exchange between the ocean and surface. Possible habitats within the ice.	Surface wave dispersion curves (for thickness) and body wave coda (for scattering/heterogeneities)	Ice thickness, sound speed, attenuation, patterns of activity (*temperature structure, impurities, locations of energy release*)
	Characterize the [global/local] thickness, heterogeneity, and dynamics of fluid layers within the ice		Seismic body and surface wave arrival times	Ice thickness, sound speed, attenuation (*temperature structure, impurities*)
			Fluid induced tremor	Fluid flow rates and volumes (*potentially habitable regions*)
	Characterize the [global/local] thickness, heterogeneity, and dynamics of the ocean	Redox state of the ocean, efficiency of redox exchange between the seafloor and ice, possible habitable niches at different depths.	Body wave arrival times	Ocean depth, structure, sound speed (*salinity, structure, temperature*)
	Determine the composition and structure of Europa's rocky mantle and the size of any metallic core	Redox state of the rock, at present and with thermal evolution through time.	Body wave arrival times	Mantle and core depth, sound speed (*mineralogy, structure, temperature*)
		Availability of thermal energy to create hydrothermal activity.	Tide induced displacement	Radial mass distribution and presence of melt in the core
		Thermal energy through time, and possible history of an intrinsic magnetic field.	Free Oscillations	Radial mass distribution and presence of melt in the core

Table 1. Candidate traceability matrix for a seismic investigation of Europa.

Suitable instrumentation exists: As recently demonstrated by Panning et al. (2017), the measured noise floor of the microseismometer that was successfully delivered for the InSight Mars 2018 mission demonstrates a sufficient sensitivity to detect a broad range of Europa's expected seismic activity. While this seismometer is designated as "short period" (in comparison to the CNES-designed very broadband (VBB) seismometer), the SP provides a sensitivity and dynamic range comparable to significantly more massive broadband terrestrial instruments. The sensor is micromachined from single-crystal silicon by through-wafer deep reactive-ion etching to produce a non-magnetic suspension and proof mass with a resonance of 6 Hz (Pike et al., 2014; 2016). The SP is well suited for accommodation on a potential Europa Lander (Hand et al. 2017), and provides an existence proof for instrumentation that might also be suitable for other landed ocean worlds missions such as the proposed Titan Dragonfly.

Formulating a seismic investigation of habitability: Table 1 shows a candidate traceability matrix for Europa with reference to the features reviewed here and summarized in Fig. 1. On other icy ocean worlds, the level of activity may be only slightly less, or perhaps more in the case of Enceladus or Titan, so the anticipated sensitivity and dynamic range would be similar. However, requirements will diverge based on the presence or absence of different phases of high pressure ice (Stähler et al., 2017; Vance et al. 2017a), and the differing extent and nature of present day activity (Panning et al., 2017). The different interior structures, and the influence of ocean salinity are explored in detail by Vance et al. (2017b). Ganymede is the only world likely to possess substantial amounts of ice VI. Titan may lack high pressure ices, and should include investigations of the atmosphere and lakes. Callisto probably has the lowest level of seismic activity and strongest scattering in its regolith, and so would require a longer-lived and more sensitive investigation similar to the of the *Lunar Geophysical Network*.

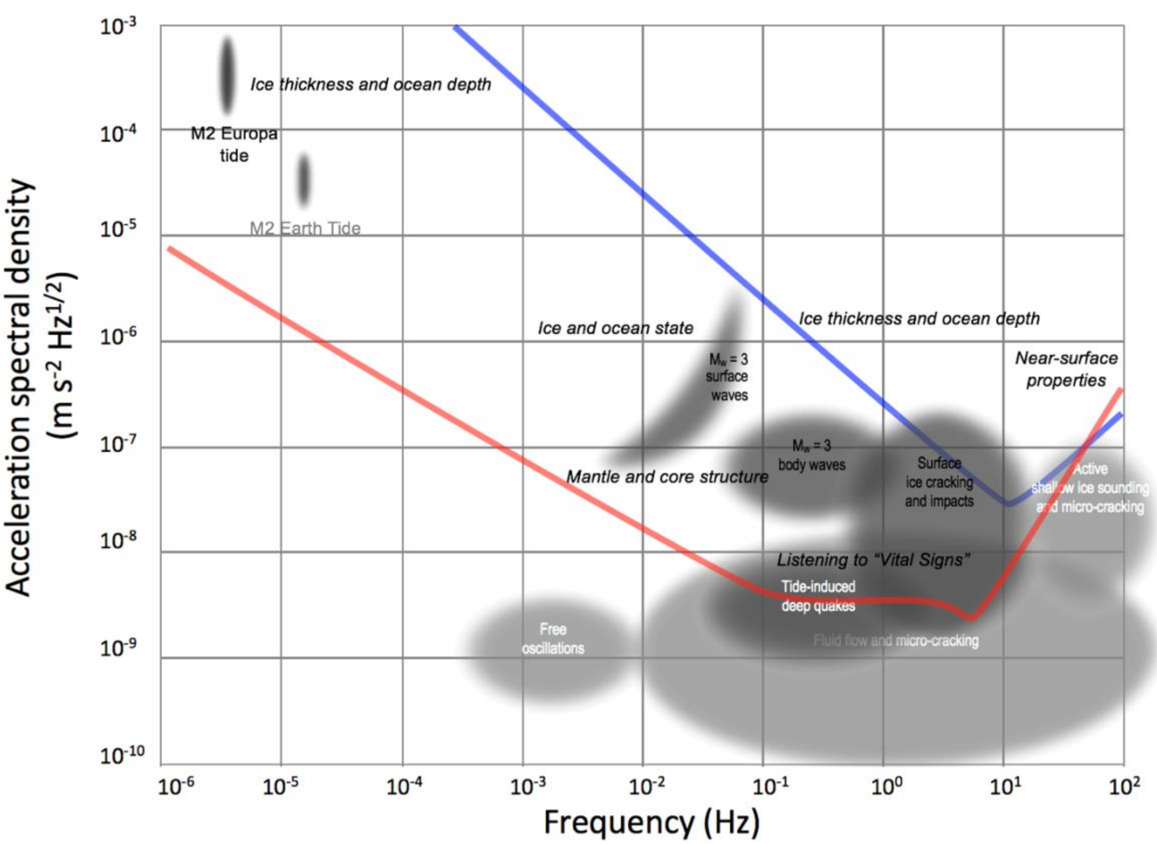

Figure 1: Europa is expected to be seismically active (Panning et al., 2006; Lee et al., 2003). A sensitive, broad-band, high-dynamic-range seismometer (red, Pike et al. 2016) could detect faint seismic signals associated with ice-quakes, and fluids flow within and beneath the ice crust to constrain chemical, and thermal structures and processes. The performance of a 10 Hz geophone is shown for comparison.

Conclusions: Seismology is the best tool for remotely investigating possible "vital signs", ground motions due to active fluid flow, in ocean worlds, yet only a handful of possible seismic sources have been considered to date. Detecting fluid-related seismic signatures similar to those on Earth would provide additional key information for constraining transport rates through the ice, and associated redox fluxes, and locating possible liquid reservoirs that may serve as habitats. Recent work draws this connection between seismology and habitability more clearly, and shows how advances in instrumentation, computational capability, and understanding of material properties will enable the needed measurements.

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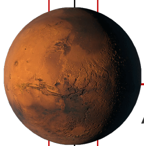

Mars Subsurface Access: From Sounding to Drilling

A White Paper Submitted to The National Academies of Sciences, Engineering and Medicine's Astrobiology Science Strategy for the Search for Life in the Universe Meeting January 2018

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1. Motivation

Access to the Martian subsurface offers an unprecedented opportunity to search for the "holy grail" of astrobiology—evidence of extinct and possibly even extant life on Mars—a journey started by the Viking landers more than four decades ago. Analyzed samples would also deliver the puzzle pieces needed to help complete our understanding of how the Martian climate, its carbonates, and its volatile inventories changed over time and may have impacted, or may have been impacted by, life.

Evidence from orbiters and rovers suggests a once "warmer and wetter" Mars [e.g., *Grotzinger & Milliken, 2012*] and recent results from the MAVEN mission demonstrated that a significant fraction of the Martian atmosphere was lost early in the planet's history [*Jakosky et al., 2017*]. As its atmosphere thinned, the flux of harmful radiation reaching the Martian surface would have increased and the surface temperatures would have cooled well below the freezing point of water. Consequently, the cryosphere would have thickened and stable groundwater would have moved to greater depths below the surface. Therefore, if Mars ever had life (regardless whether it emerged on or below the surface), then it should have followed the permafrost/groundwater interface to progressively greater depths where stable liquid water can exist. There, shielded from seasonal and diurnal temperature effects as well as from harmful effects of ionizing radiation, it could have been sustained by hydrothermal activity, radiolysis, and rock/water reactions. Hence, the subsurface represents the longest-lived habitable environment on Mars. Therefore, in comparison to the surface, our chances of finding signs of extinct life are much greater in deep, protected, self-sustaining subsurface habitats that putative organisms might have inhabited [e.g., *Michalski et al., 2017*].

If extant life exists on Mars today, then the most likely place to find evidence of it is at depths of a few hundred meters to many kilometers, where groundwater could persist despite today's low geothermal gradients [*Clifford et al., 2010; Grimm et al., 2017*]. Moreover, while the preservation of molecular biosignatures on Mars is debated, the consensus is that detection at depths greater than a few meters is favored because of the shielding from harmful radiation [e.g., *Kminek and Bada*, 2006; *Pavlov et al., 2016*].

Additionally, accessing information in the Marian subsurface (geochemical, geophysical, and astrobiological) to obtain subsurface profiles of the D/H, $^{18}O/^{16}O$, carbonate content, organics, pH, volatiles, redox conditions, porosity, permeability, temperature, and stratigraphy—unaffected by atmospheric processes or solar/cosmic radiation—will enable us to much better constrain the environment for life over geological timescales, i.e., the time-dependent variation of water loss, climate, volcanism, and tectonic processes.

Therefore, the exploration of the full potential of extinct or extant life on Mars and its environmental context over the last few billion years requires accessing the deep subsurface, and the collection of samples—starting a few meters below the surface but ideally reaching the putative modern day stable water table at hundreds of meters to kilometers depth.

We now have the capability to achieve this goal, specifically due to (a) recent technological advances, (b) an improved understanding of the local variability of Martian environments, and (c) increasing commercial, international, and human opportunities on Mars (see Figure 1):

a) technological advancements in miniaturization, automation, data processing, sensor-driven adaptation, fault protection and recovery, and instrumentation for chemical characterization of soluble, gaseous, and solid compounds can make *in situ* deep subsurface exploration and wide high resolution subsurface sounding for volatiles down to a few km of depth feasible,

b) latest scientific results on the 3D diversity of Martian surface and, increasingly, subsurface environments facilitate more rigorous landing site selection and the correlation of local results within a global context, and,

c) emerging commercial, international, and human opportunities on Mars enable out-of-the box approaches: commercial collaboration opportunities through, e.g., SpaceX, could provide flights to Mars every 2 years, possibly as early as 2022; growing international interest in Mars exploration by the Emirates, India, China, and Japan in the early 2020s can broaden international collaborations; and NASA's & SpaceX's plans of sending humans to Mars in the 2030s call for mapping Martian resources and the astrobiological potential of the subsurface.

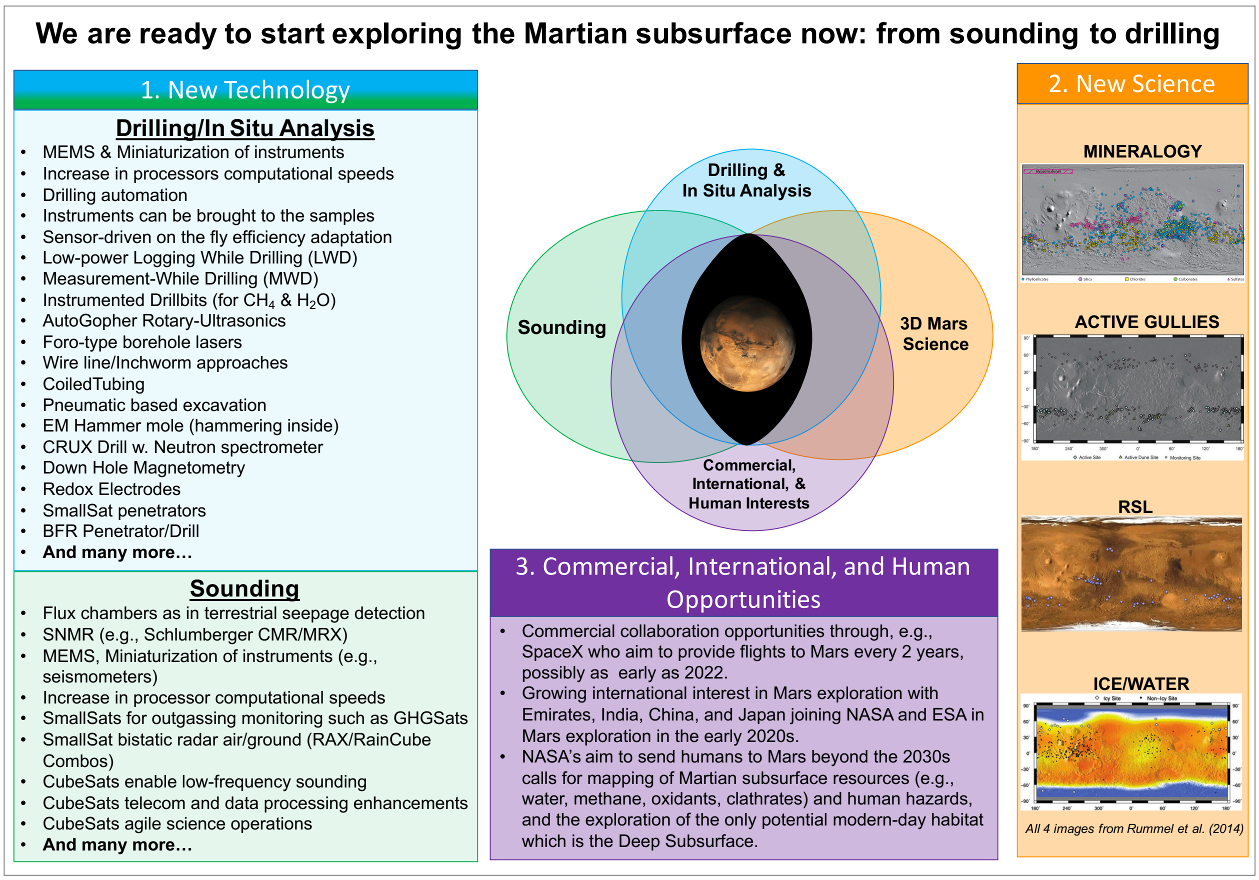

Figure 1: Three aspects that make vigorous Mars subsurface exploration feasible today: 1) *Technological advancements in drilling & sounding—driven by miniaturization, automation, increased computational speed, sensor-driven adaptation, and in situ analysis have significantly reduced power, size, and mass footprints and created new tools for subsurface exploration* [*Chu et al., 2014; Davé et al.*, 2013; *Grimm*, 2003; *Zacny*, 2007a; b; *Zacny et al.*, 2008; *Zacny et al., 2016*], ***2)*** *New scientific achievements, from mapping of aqueous minerals, active gullies, recurring slope lineae, ice and water deposits (showing water-equivalent hydrogen as background color and ice-exposing new impacts) allow us to know better where and how to drill [Dundas et al., 2014; Ehlmann and Edwards, 2014; Ojha et al., 2014; Rummel et al., 2014; Stuurman et al., 2016; Wang et al., 2013]; this scientific progress will be improved by ExoMars TGO, which will help to localize potentially biologically relevant zones of interest such as methane seeps, and* ***3)*** *commercial, international, and human opportunities [Wooster et al., 2007; Hoffman, 2015, 2016] create a powerful paradigm shift and out-of-the-box opportunities for the search for life on Mars.*

2. Past and current efforts towards deep subsurface access

So far, strictly scientific motivations for Mars subsurface exploration have taken a back seat to exploration of the Martian surface. The most recent studies and workshops on Mars Drilling (>10 meters) date back to 2000/2004 [*Blacic et al., 2000; Miller et al., 2004*]. These studies recommended that progress in autonomy, mass reduction, and *in situ* measurements as well as candidate instrument types are required to make deep drilling and Mars subsurface exploration feasible. Since then great progress has been made enabling us to now identify mission concepts and instrumentation needed to achieve Mars subsurface access [see Figure 1, Sections 3-4, and *Chu et al., 2014; Davé et al.*, 2013; *Grimm*, 2003; *Zacny, 2007a; b; Zacny et al., 2008, 2016*].

Missions including ESA's ExoMars rover in 2020, NASA's Insight in 2018 and Mars 2020 will soon begin our exploration of the very shallow subsurface. To date, NASA has no plans of pursuing sampling at depths greater than ~10 cm. The Mars 2020 mission will collect shallow samples (~6 cm) for potential return to Earth.

In the report "Mars Exploration 2009-2020" [*McCleese, 2003*], a subsurface mission to find extant life was identified as a high risk but necessary mission in the 2020 timeframe, and as NASA begins to consider future human exploration of Mars and in situ resource utilization [*Hoffman*, 2015; 2016], opportunities to develop systems with greater capabilities to explore the Martian subsurface are emerging and gaining support within the NASA community. *Beaty* [2015] recommends in the report "Scientific Objectives for the Human Exploration of Mars Science Analysis Group" a focus on strategies to access the subsurface. In the report "Mars Science Goals, Objectives, Investigations, and Priorities: 2015", this recommendation is extended by additionally calling for global screening related to subsurface habitability [*Hamilton et al.,* 2015].

3. Specific technologies or recent scientific developments that make a compelling case for accessing the Mars subsurface

Deep subsurface mission concepts can capitalize on recent technological efforts aimed at advancing miniaturization, automation, data processing, sensor-driven adaptation, and fault protection and recovery technology. Such progress allows adaptive and automated deep drilling in various soils and simultaneous *in situ* analysis (see Section 4). It also enables CubeSat or SmallSat obiters/helicopters/planes to monitor greater surface areas for small-scale seeps, fissures, or subsurface volatiles with smaller footprints and costs than typical orbital missions allowing access to sites that rovers cannot reach.

Next to this game-changing technological progress, our expanded understanding of the Martian surficial and sub-surficial variability will facilitate mission planning, specifically site selection by providing better *a priori* subsurface information (see Figure 1). For example, high-resolution orbital images have already provided numerous examples of locations with natural entrances into the Martian subsurface, such as lava tubes, ice caves, or even highly fractured terrain that could be gas (e.g., methane) seeps [e.g., *Boston et al., 2011*; *Oehler and Etiope, 2017*].

The recent entrance of the private sector into the space exploration arena could also enable faster and deeper access to the subsurface. For example, a variant of the Dragon space capsule (SpaceX) could be refitted to SpaceX's BFR transporters planned to launch to Mars as a low-cost, large-capacity, near-term, Mars lander that is well suited for deep drilling missions due to its ability to accommodate a long drill string and to provide ample payload space for sample processing and analysis [*Heldmann et al. 2017*].

4. Autonomous deep drilling technology and sample collection

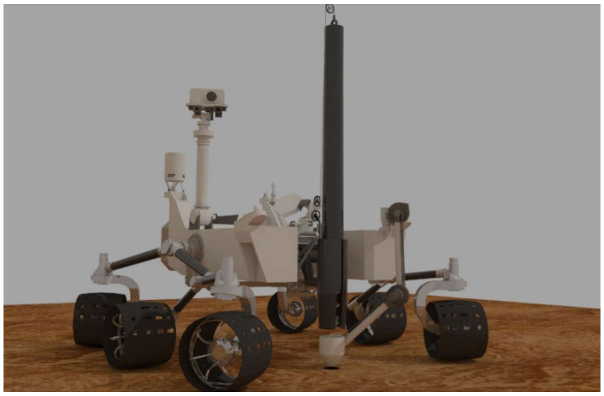

Figure 2: *WATSON drill with integrated Mars2020 Sherlock instrument could be used to penetrate 1 km depth.*

The technologies for terrestrial subsurface resource characterization and extraction are already developed for harsh environments (low/high temperature and the high shocks that the equipment could be subjected to during launch, landing, and drilling operation). Continual advancements in drilling, completion, and rig technology from the oil, gas and water service industries have enabled significant progress to be made in addressing the specific issues of Martian subsurface characterization (via seismic, electromagnetic and ground-penetrating radar, in addition to other techniques, including potentially gravity gradiometry), remote drilling, and borehole stability. Also, significant progress has been made in clean drilling and avoiding/detecting contamination in drill cores of ancient rocks on Earth [e.g., *French et al., 2015*] and additional enhancements in life-compatible drilling technologies might be expected to follow from the International Continental Scientific Drilling Program (ICDP)'s growing interest in life-inspired drilling [*Kieft et al., 2015*]. Next generation drills, like WATSON [*Eshelman et al., 2017*] currently deployed in terrestrial cryoenvironments could be deployed from a Curiosity size rover and penetrate the subsurface to approx. 1 km depth (see Figure 2).

5. Recommendations

- Support the development and field testing of technologies for automated drilling in bedrock to depths of hundreds of meters to kilometers.
- Support the development of sample collection techniques from depths below the radiation-processed regolith and down to the water table for astrobiological analysis.
- Support development for sampling material from special subsurface regions (i.e., water or ice) to meet all *Planetary Protection* requirements.
- Support the development of technologies for access and exploration of existing underground spaces (e.g., lava tubes, caves).
- Support the development and miniaturization of low-cost subsurface sounding technologies for determining the subsurface volatile, clathrate, and fluid inventories—such as but not limited to electromagnetic, ground-penetrating radar, and seismic.
- Support theoretical, computational, experimental, laboratory, and field work on terrestrial analogs that facilitates a better understanding of the Mars subsurface diversity (geophysical, geochemical, geological, hydrological, and potentially biological) from local to global scales—such as the local potential to sustain liquid water and redox-rich environments.

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White Paper for Consideration in the Development of NASA's Astrobiology Science Strategy for the Search for Life in the Universe

LACUSTRINE MICROBIALITES: THE IMPORTANCE OF FORMATIVE CONDITIONS & BIOSIGNATURE CHARACTERISTICS IN MARTIAN SAMPLE SELECTION

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Summary: We identify research questions regarding the roles of biology and the physiochemical environment on lacustrine microbialite formation and preservation. These avenues of inquiry inform biosignature search strategies for Mars and address the feasibility of rover instruments in biosignature identification, with implications for sample return.

In the search for candidate biosignatures on Mars, lacustrine environments have long been recognized as having excellent potential for both habitability and preservation [e.g., Summons et al., 2011]. Unsurprisingly, most recent, current and future Mars landing sites—including the remaining three Mars 2020 sites—are proposed locations of former lacustrine environments [e.g., Gale crater, Grotzinger et al., 2015; Jezero crater, Schon et al., 2012]. Despite work investigating terrestrial lacustrine environments, there remain substantial gaps in our understanding of the complex interplay between processes and local environmental conditions, and the influence of these factors on the presence, character and preservation of biosignatures (Figure 1). In this white paper, we outline critical research pathways for understanding the processes that lead to mineralized lacustrine microbialites. These research objectives will aid the creation of comprehensive models for lacustrine microbialites that encompass the development of microbial communities, the formation and distribution of macroscopic structures, and their modes of preservation. In the absence of such models to optimize sampling strategy, there is the potential to misguide martian landing and sampling site selection, as well as possibly miss or misidentify critical biomarkers.

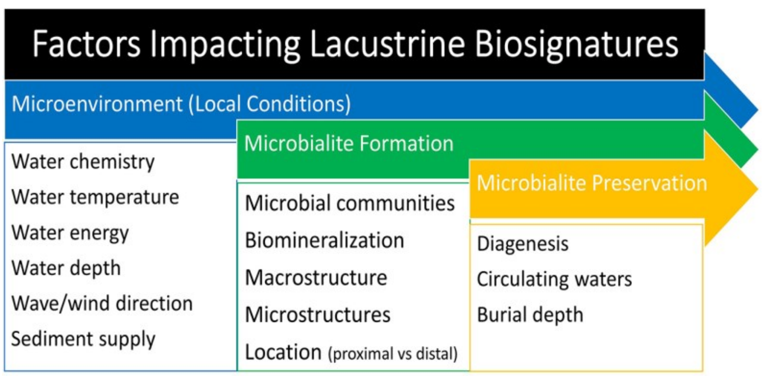

Figure 1: A more complete understanding of the complex interplay between micro-environmental conditions and the processes involved in the formation and preservation of microbialites is needed to inform biosignature search strategies on Mars.

Research on the identification of potential martian biosignatures ranges from the orbital detection of potential metabolic byproducts, such as methane, to the *in situ* identification of specific organic compounds (biomarkers) that derive from microbial metabolism. A primary difficulty in biosignature identification, however, lies in the determination of syngenicity—how certain can we be that organic materials preserved in a sedimentary rock are directly associated with the host rock and its inferred depositional environment? Microbialites, however, are organo-sedimentary structures that result from the direct interactions between microorganisms and their aqueous environments via microbially or environmentally induced mineralization, or by trapping and binding of detrital particles. These mechanisms result in an array of potential biosignatures (e.g., macrostructures, microstructures, biomineral precipitates) depending on local environmental conditions and, potentially, the type of microorganisms present.

The majority of microbialite research has concentrated on marine settings (Figure 2A) in carbonate-dominated tidal flats and marine shelves, as well as deep ocean vents. Non-marine environments that foster microbialites include fresh-water spring systems (e.g., hot springs and travertine systems), cave deposits, and a range of fresh- to hypersaline- to alkaline lake systems. Terrestrial systems, however, are far more variable environments than their marine counterparts.

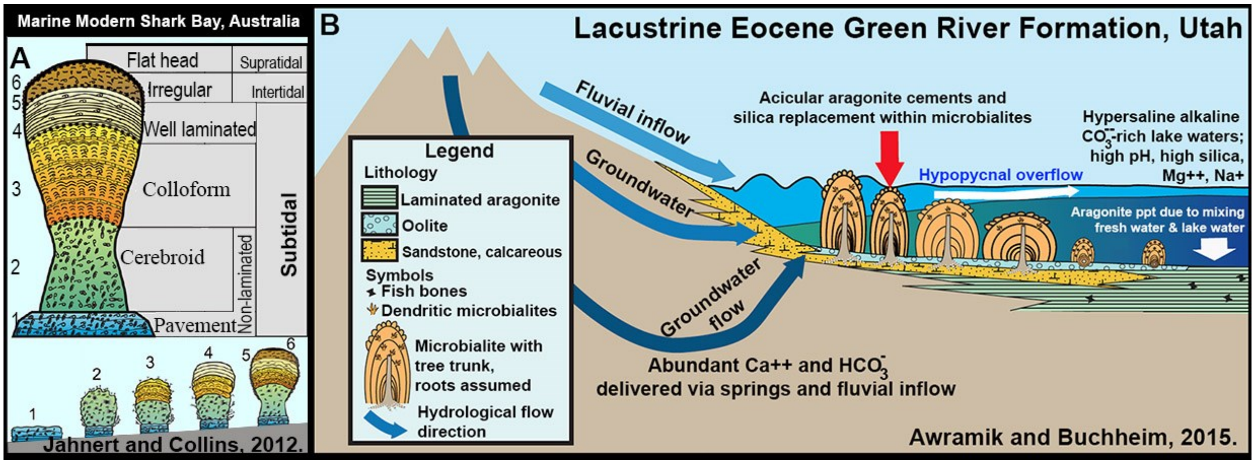

Figure 2: Examples of diverse microbial morphologies and fabrics associated with variations in water energy, depth, water chemistry, nutrient supply and substrate gradient for A) a marine environment at Shark Bay, Australia, and B) a lacustrine environment preserved in the Green River Formation in Utah, U.S.A. Figures are modified for legibility.

A critical element in the development of a targeting model is an understanding of how consistently microbialite morphologies vary across lacustrine environments. Although microbialite morphology broadly reflects water depth (Figure 2B), the complexity of observed morphological diversity may also reflect the inherent environmental variability of lacustrine systems. To accurately predict the most promising sampling locations associated with martian lacustrine deposits, the general trends in the spatial distribution of microbialite occurrence and preservation need to be identified across a diverse sampling spectrum of lacustrine environments on Earth.

Research must continue to encompass the full range of terrestrial lacustrine microbialites to ensure a comprehensive understanding of all the factors that influence morphology, composition, and structure of microbialites and their associated biosignatures. Lacking a holistic approach to examining terrestrial microbialites, there is a risk of prejudicing results by concentrating only on modern and ancient terrestrial lacustrine locales that are perceived to reflect comparable martian conditions (past or present). Where possible, the community needs to document the link between lacustrine microbialite features and attributes observable in rover data, such as outcrop-scale macrostructures (domes, ridges, rings, laminae, etc.), position within the littoral zone (onshore versus offshore facies, relationship to deltaic lobes, etc.), or chemical signatures (e.g., biomarker organic molecules, chemical features that suggest biological processing). Without such observational criteria, significant mission operations time will be needlessly expended on reconnaissance within regions of interest to identify optimal sampling sites. Moreover, if putative microbialites are identified, we risk not being able to attribute their formation to biological processes.

Furthermore, recent landing site selections for NASA and ESA missions have been heavily influenced by the prevailing current opinion that the longest habitable window on Mars was during the first half billion years [e.g., Carr and Head, 2010; Vago et al., 2017]. Climatic conditions were conducive to the sustained presence of surface water on Mars during the Noachian (~4.1 to 3.7 Ga), comparable to conditions on Eoarchean Earth prior to the advent of photosynthesis. Less habitable surface conditions apparently prevailed on Mars in the Hesperian and Amazonian, with intermittent periods of surface aqueous activity. Therefore, there is a need to study the potential for microbialite formation by non-photosynthetic processes as well as putative processes that might lead to their preservation.

Lacustrine microbialites vary widely in their morphology, microstructure (internal fabric), mineralogy and geochemistry depending on local environmental conditions and the composition of distinct microbial communities (Figure 2) [Grotzinger and Knoll, 1999]. Local environmental conditions influence the abundance and type of microorganisms, their distribution, and their spatial heterogeneity within the rock record, as well as the construction of macroscopic (i.e., morphology) and mesoscopic (i.e., textural) microbial features. The presence of specific microbial metabolisms (e.g., photosynthesis, sulfate reduction) can also influence macroscale features by effecting mineralization within the microbial communities.

One of the most critical elements of lacustrine microbialites, which at present remains poorly understood, is the relative influence of various driving factors on patterns of growth and preservation. Listed below are some of the key outstanding questions and areas of inquiry.

- How consistently do microbialite spatial patterns vary across environmental gradients such as proximity to shore, water depth, water chemistry, wave energy, sediment supply, fluvial input or groundwater inflow (e.g., Figure 2B)?
- To what extent do local environmental conditions (e.g., potential seasonal mixing of lake water with ground- and surface waters of different chemistries, extent of evaporation, and rate of sediment influx) influence mineralization of microbial features and, therefore, determine both their spatial preservation and their mesoscale structure (Figures 2B and 3)?
- Although it is clear that lake chemistry (e.g., temperature, acidity, salinity, metals composition) will affect microbial compositions, we have limited understanding regarding the extent to which specific microbial species and their metabolisms can affect microbialite microstructure relative to primary growth fabrics or mineralization. Moreover, can the chemical and isotopic signatures preserved in microbialite deposits be used to infer the geochemistry of their host aqueous environment (e.g., Newell et al., 2017)?
- The majority of modern lacustrine microbialites show associations with bathymetry, and by inference light penetration. In the absence of sunlight, what is the role (if any) of chemotrophic microorganisms in microbialite formation?
- What is the continuum of microbialite morphologies associated with various evolutionary sequences? For example, discrete formation episodes may impact the resulting microbialite morphology. Domal microbialites can collapse during dormant periods (e.g., associated with a fall in water level), creating a ring structure (Figure 4) that can influence subsequent patterns of microbial growth [Vanden Berg et al., 2016].
- Despite prodigious work investigating the role of microorganisms in the nucleation and precipitation of minerals, it remains uncertain whether these effects are recognizable in the rock record, and the degree to which the microbial influence may be overprinted by the effects of local chemistry and diagenesis. What chemical or isotopic signatures in lacustrine deposits can be attributed directly to the existence of microorganisms, especially those obtainable from rover instruments?

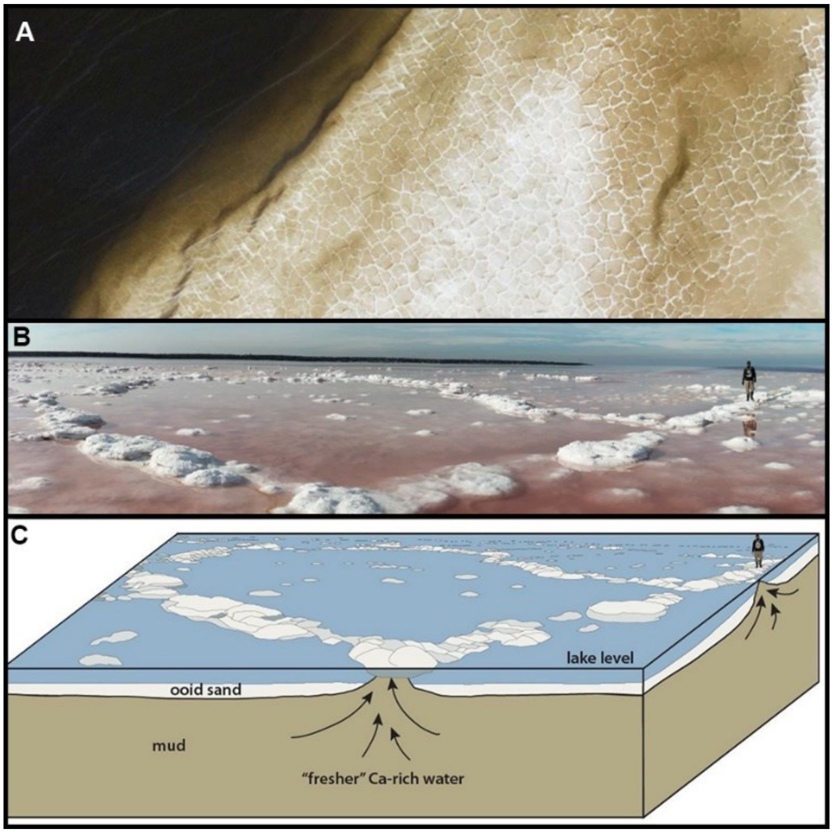

Figure 3: (A) Halite-encrusted microbial domes are associated with the perimeter of desiccation megapolygons (10-85 m diameter) as seen in this satellite image near Promontory Point, Great Salt Lake, Utah, U.S.A. (B) Microbialites are concentrated on the slightly elevated topography around the perimeter of the polygons created by upwelling mud. (C) Nutrient-rich groundwater rising along the edge of the upwelling mud may help mediate microbial growth. [Vanden Berg et al., 2016].

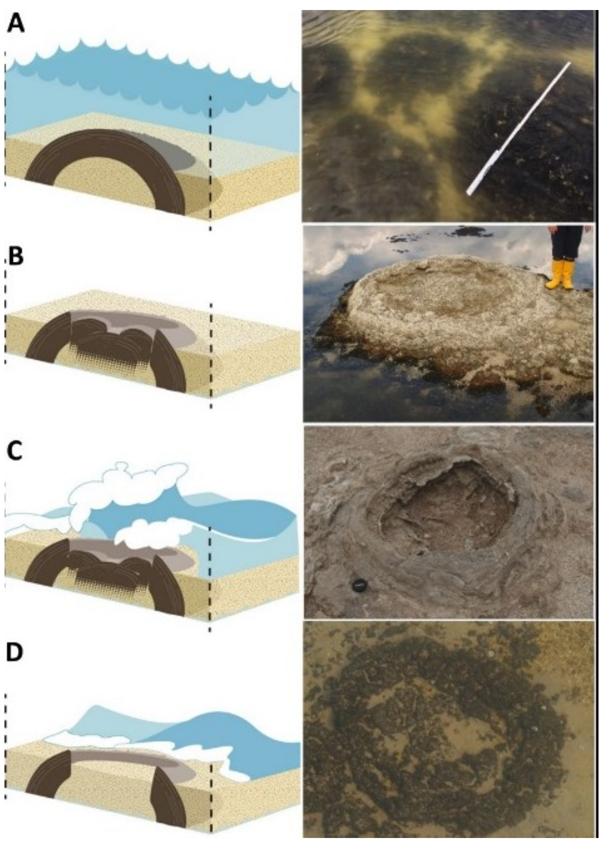

Figure 4: Stages in hypothesized origin of microbialite rings found in Great Salt Lake, Utah [Vanden Berg et al., 2016]. Microbialite domes (A) have a partially lithified outer shell and unconsolidated interior that is susceptible to collapse (B) when lake level drops. After collapse, wave action (C) removes broken material from the center and leaves behind the raised outer ring. When lake level rises, microbes re-colonize the old, eroded ring structure (D). Microbial mats attached to these structures are dominated by halophilic, phototrophic cyanobacteria [Lindsay et al., 2017].

- In terrestrial carbonate depositional systems, five precipitation modes have been identified as a function of salinity versus alkalinity, and these mineralization modes are tentatively linked to microbialite microstructure [Chagas et al., 2016]. Because of the variability in lacustrine environments, we must also examine whether carbonate-dominated microbialites can serve as reasonable proxies for microbialites preserved by other mineralogies, such as silica (chert) or sulfate (gypsum/anhydrite).

We conclude that further study of the role of various drivers on lacustrine microbialite formation and their preservation is critically important in addressing how uniquely a set of observations can be attributed to biological processes. Combining field-based observation with laboratory analyses will provide pathways to evaluate the likelihood that lacustrine biosignatures observed with rover instruments can be identified and distinguished from abiotic sources. Martian sample return will be necessitated if the diagnostic criteria requires using techniques not available on rover platforms (e.g., stable isotope ratios, spatially constrained geochemical and isotopic analyses, and especially examination under extremely high magnification, such as thin section petrography and scanning electron microscope, SEM).

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A UNIVERSAL APPROACH IN THE SEARCH FOR LIFE AT THE MOLECULAR LEVEL

A White Paper in response to the
ASTROBIOLOGY SCIENCE STRATEGY FOR THE SEARCH FOR LIFE IN THE UNIVERSE

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White Paper Description (350 Character Max)

Molecular-level analysis is the most effective and least ambiguous approach to the search for extraterrestrial biosignatures. Combining gas-, solid-, and liquid-based techniques coupled to mass spectrometry analysis provides the best chance of acquiring compelling evidence for life on other worlds in our solar system.

Reassessment of State of the Art in Life Detection

The current NASA Astrobiology Strategy Report (2015) contains a section in Chapter 5 entitled "Current Techniques and Strategies for Life Detection" which leaves room for a significant revision in light of recent scientific and technological advancements. The report describes how life detection strategies had been primarily focused on "life as we know it". However, a broader, more open-ended perspective acknowledged that 1) signs of extant life could be found by measuring parameters sensitive to chemical disequilibria, 2) other chemical forms of life could be possible, and 3) "the theories on how to search for this 'weird' life are diverse, though development of a more universal protocol might be possible."

These points were further developed in considerable detail in the Europa Lander Science Definition Team (SDT) Report (2017), which provides a blueprint for a universal life detection protocol. This report identifies a set of chemical and other measurements that enable the identification of extant life, be it "Earth-like" or "weird" (i.e., not necessarily based upon the exact biochemical building blocks, structures, and processes of terrestrial biology). Briefly, the report posits that of all the possible approaches to life detection in our solar system, the most compelling evidence is secured through the search for biosignatures at the molecular level. On planetary missions, these biosignatures could be sought directly from a physical sample *in situ* using techniques that take a holistic approach to assessing the chemical inventory. This would be possible by not only searching for the presence of known, potentially biogenic organic molecules (such as proteins, DNA, RNA, etc.), but also by capturing a broadly representative chemical profile of the population of molecular species and structures. Through the identification of these molecules, and determination of their relative abundances and structural correlations as a set, patterns begin to emerge that can help distinguish between abiotic and potentially-biogenic chemical processes. These include levels of intrinsic complexity, ligand and carbon-number patterns, and distributions within classes of organics, including stereochemical properties (e.g., large enantiomeric excesses across a collection of amino acids). This approach, in which *relative populations of molecules and molecular properties* are measured objectively, enables a thorough, low-ambiguity means for biosignature identification.

Enacting a semi-exhaustive and universal molecular search for life on an astrobiology mission presents significant technical challenges, and necessitates new, highly-integrated approaches to be implemented in space-ready instrumentation. A list of potential technologies for chemical analysis was provided in the NASA Astrobiology Strategy Report (2015). Although it was not intended to be a complete list, there are some notable omissions that deserve explicit discussion. For the identification of molecules in an unknown sample, there remains no more powerful or universal technique than mass spectrometry (MS), and this is well described. MS has a long history of successful spaceflight implementation and scientific discovery on many planetary missions. Each environment and mission opportunity levies unique challenges and requirements on a mass spectrometer investigation, with a key mission-specific factor being the proper design of the sampling "front end" of the MS, as this is the interface between the sample and its analytical detector. As such, a key point of the Europa Lander report is that in order to compile *the broadest possible inventory* of organic molecules required for a universal search for life, the investigation must efficiently transfer *a statistically unbiased majority* of the sample's native organics into a mass spectrometer where they can be analyzed.

Indeed, the extraction and transfer of the full range of organic molecules is truly the "missing link" of robust MS-based molecular analysis of entirely unknown samples, and by extension, life detection in general. This is because organic molecules can exist with a vast array of chemical and physical properties. One such chemical parameter that strongly determines the optimal route to transfer a molecule into a mass spectrometer is its polarity (i.e., separation of charge within the molecule itself). Non-polar molecules tend to exhibit a largely homogeneous distribution of elemental constituents; examples include molecular oxygen and aliphatic hydrocarbons. In contrast, polar molecules such as carbon monoxide, amino acids, and carboxylic acids tend to have more elemental heterogeneity leading to asymmetry and the formation of poles. Gas chromatography-MS (GC-MS) is readily amenable to the analysis of non-polar, volatile, and semi-volatile molecules; however, it is challenged when presented with polar, water-soluble, less-volatile organics. For the water-soluble fraction, liquid-based separation techniques are analogous to GC in their ability to sensitively and quantitatively elucidate molecular structure when coupled to MS. This capability will be particularly important on missions to ocean worlds such as Europa or Enceladus where a spectrum of complex water-soluble organic molecules would be expected to govern the potential emergence of life and its biochemistry. To complement front-end separation-based approaches, laser desorption-MS (LD-MS) can be used for the analysis of large (up to kilodalton range), nonvolatile molecules such as peptides and macromolecular organics, with detection limits of femtomoles and below.

The Way Forward for Astrobiology Missions to Ocean Worlds

For practical chemical reasons, and to provide the degree of certainty only achievable with independent measurements, the optimal life-detection technology comprises a suite of instrumentation with multiple means for teasing apart a sample and introducing it into a mass spectrometer. Ideally, the mass spectrometer would accept samples in any phase, be it gas, liquid, or potentially by direct desorption from a solid substrate. Given the high technology readiness level (TRL) for analysis of evolved gases from bulk samples via GC-MS, and from the surfaces of solid samples using LD-MS, the time is ripe for the development and deployment of complete, integrated instruments that combine multiple sampling capabilities. To complement the gas- and solid- phase techniques, significant new capabilities for the analysis of liquids have been developed since the writing of the last Astrobiology Science Strategy Report (2015). We provide a particular focus on these advancements below.

Advances in Liquid Sample Handling, Separation, and Analysis

Significant progress in liquid sample handling, liquid separations, and interfacing liquid sample front ends to mass spectrometers has been made since 2015. These functionalities are ready for incorporation into a MS-based instrument suite in order to provide the remaining capabilities needed for the most exhaustive, universal search for life at the molecular level.

Liquid Extraction

Subcritical Water Extraction (SCWE) uses liquid water as an extractant at temperatures above the atmospheric boiling point of water (373 K, 0.1 MPa), but below the critical point of water (647 K, 22.1 MPa). Under these conditions, the chemical properties (permittivity, viscosity, ionization constant, and surface tension) of the water are modified, making it a powerful solvent for extraction of both polar and non-polar compounds. Previous work in this area used SCWE to release amino acids from Atacama Desert soils.[1,2] Recently, a compact, integrated sample extractor has been developed for in situ SCWE.[3] This system is capable of accepting a sample in a crucible, connecting the crucible to a liquid interface to introduce water to the sample, then heating to 250 °C. Following a predetermined amount of time the liquid interface is once again engaged and the water extract is collected for analysis. This prototype was successfully tested in the Atacama Desert, Chile in 2017 as part of an ongoing PSTAR effort.

Liquid Sample Handling: Autonomous Microfluidic System Development for Space Flight

The past decade has witnessed a series of technical advancements in fluidic sample handling and analysis for space, through research and development of nanosatellites for biology and astrobiology studies.[4-9] This technology is currently being adapted for a variety of astrobiology mission scenarios. Sample handling is implemented through the use of monolithic microfluidic “sample processors” that receive a sample and execute a sequence of chemical and physical manipulations. This sample can then be delivered to a suite of sensors and instruments, thereby enabling each assay to operate under conditions of optimal performance.

These systems leverage the immense body of development in the microfluidics and “lab-on-a-chip” disciplines that has found field application in areas ranging from industrial process control to point-of-care biomedical assays. Microfluidic systems benefit from recent advances in miniature, micro-, and nano-technologies that include everything from polymer (micro)fabrication to integrated optics to high-performance sensors and materials for extreme environments. Examples of some of the fluidic functions performed by these sample handling subsystems include: 1) storage and reconstitution of dry reagents, labels, dyes, calibration standards, or sample blanks; 2) dissolution/dilution of liquid samples; 3) particulate filtering; 4) liquid sample degassing; 5) pH adjustment via mixing with buffers; 6) sample concentration.

Microfluidic Chemical Analysis and Capillary Electrophoresis

Recent developments include the design and optimization of new analytical methods utilizing capillary electrophoresis coupled to laser-induced fluorescence detection (CE-LIF). These methods expand the science achievable with the CE-LIF technique by increasing the number of organic compounds we can detect and quantify. This includes methods for analyzing sulfur-containing compounds,[10] the use of non-aqueous solutions for analysis of long-chain amines and fatty acids by CE,[11] and most importantly a recent major expansion of the state of the art in chiral amino acid analysis.[12] In particular, a complete separation of twelve astrobiologically relevant amino acids (including five chiral pairs) was demonstrated with limits of detection as low as 5 nM in raw samples taken from Mono Lake, CA. Despite the high salinity of the lake water, no sample preparation beyond “mix and analyze” was required. Additionally, method development for CE using other forms of detection are also underway, including CE-MS of organics in aqueous samples containing extremely high levels of salts, and simultaneous detection of amino acids and inorganic ions dissolved in liquid samples by CE-C^4D (Capacitively Coupled Contactless Conductivity Detection).

Efforts also include a TRL analysis of electrophoresis and supporting instrumentation for spaceflight applications,[13] as well as the development and validation of the most advanced and capable automated microchip electrophoresis instrumentation, the Chemical Laptop.[14] This battery-powered portable instrument is capable of automatically performing all fluidic manipulations required for end-to-end analysis of amino acids. As part of an ongoing PSTAR effort, the system was successfully tested in the Atacama Desert, Chile in February 2017.

Capillary Electrophoresis-Mass Spectrometry Instrumentation Development

The first automated CE instruments were commercialized in 1989, and now represent a market of more than $1.5 billion U.S., being sold as routine analyzers in the diagnostic, forensic, industrial, biopharmaceutical and life science research sectors. For molecules to be analyzed by MS following separation by CE, they must first be converted from a molecule in liquid phase to an ion in gas phase. The most efficient way to achieve this is via electrospray ionization (ESI). As this approach integrates CE and ESI into a single process, the term CESI has been coined to describe the function. Because the performance of ESI significantly improves with a reduction in flow, by using CESI a much higher MS sensitivity is obtained,[15] enabling the extremely demanding limits of detection described in the Europa Lander SDT Report.

Advances in Mass Spectrometry of Gaseous and Solid Samples

Spaceflight MS, particularly for molecular analysis of planetary samples, has continued to advance to meet the ambitious objectives of current and future missions. The Sample Analysis at Mars (SAM) quadrupole MS has enabled the seminal detection and quantification of organic compounds and other species at Mars through atmospheric, evolved gas analysis, and GC-MS modes.[16] The ultimate power of the SAM investigation is its tight integration of multiple measurements on a common sample within an integrated “lab”. The Mass Spectrometer for Planetary Exploration (MASPEX) investigation on the Europa Clipper mission will perform a sensitive, high-resolution molecular analysis of the Europan exosphere, and sample any potential plumes, on the multiple close flybys of that mission.[17] On the ExoMars rover, planned for a 2020 launch, the Mars Organic Molecule Analyzer (MOMA) will carry out a broad analysis of potential organics in samples obtained by a two-meter-long drill. By combining GC-MS with LD-MS, along with tandem MS for molecular structural analysis, MOMA will support the ExoMars objective of seeking potential molecular biosignatures in ancient Martian terrain – the first mission to search deliberately for Martian life since the Viking Landers.[18]

Summary and Future Outlook

The fusion of high-TRL, flight-robust MS with a host of new liquid chemical processing and analysis techniques provides our best possible chance of positively and unambiguously identifying biosignatures on other worlds, should they exist. The instrument-suite development approach described here (Figure 1), broadly speaking, would need to be tailored for the specific range of unique environmental conditions during spaceflight and operations (for example, the extreme radiation of Europa’s surface). Additionally, such instrumentation for astrobiology missions would be subject to highly stringent planetary protection and contamination control requirements. Yet, despite the remaining challenges facing this type of ambitious instrument concept, an achievable goal for the coming decade would be to mature this technology and deploy it on a mission seeking signs of life in either Europa or Enceladus.

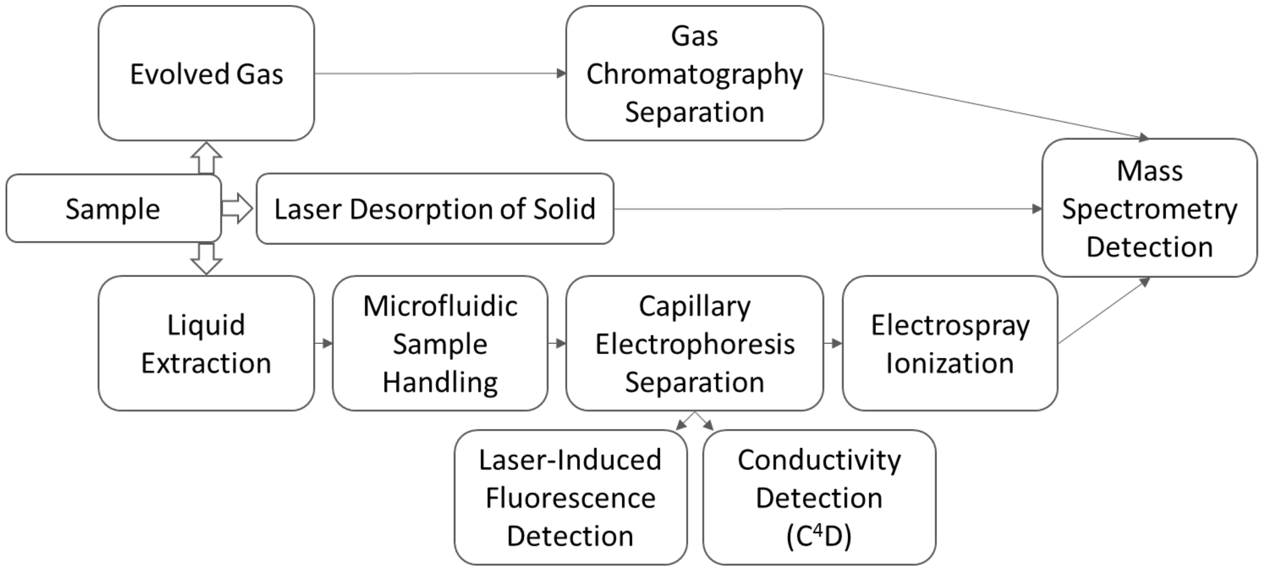

Figure 1. An MS-based instrument suite capable of analyzing gas, liquid, and solid samples representing a broad and robust approach to analysis of potentially-biogenic organic molecules

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White Paper submission to:

Space Studies Board.
Astrobiology Science Strategy for the Search for Life in the Universe

Title:
Sample Collection and Contamination management for Life Detection in Ocean Worlds during Plume Fly-throughs

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1. Introduction

Life detection missions to Ocean Worlds and Plume Fly-throughs

Robotic missions to the Ocean Worlds of Jupiter and Saturn, such as Europa and Enceladus, have been recently proposed to focus on life detection. These missions could involve: landing and drilling through the ice shell [1] into the underlying ocean to obtain samples. More likely, future missions could land near a plume and collect surface samples of ocean ice deposited around the plume, or fly-throughs to collect plume samples. Plume fly-through is the easiest option to obtain samples of the moons' ocean beneath the ice shells because these plumes are jetted into space. Plumes, jets of H_2O ice grains from the underlying ocean, have been well mapped on Saturn's moon Enceladus [2] and, most recently, detected on Europa by the Hubble Space Telescope [3]. The opportunity for life hunting on Europa are encouraging: whether the icy shell is thin, ~3 km [4] or thick, 25-30 km [5-6] it is plausible that the interaction between the shell and the pelagic ocean could support life.

Regarding Enceladus, the Cassini spacecraft flew through the Enceladus plumes at speeds > 7 km/sec. Cassini's instruments detected organics, salts, and gases in the plasma generated by the high speed impact with plume ice grains. Unfortunately, organic molecules were destroyed or altered in this process making difficult to characterize the organics. Slower ice collection speed (~2 km/sec) plume fly-throughs, will provide significantly better science as pristine ice particles can be collected with biomarkers intact for onboard analysis. Likewise, landing near a plume and collecting surface samples could similarly provide pristine ice samples with intact biomarkers.

Two different fly-through missions were proposed to NASA's New Frontiers 2016 Announcement of Opportunity to search for life in the Enceladus icy plumes by collecting ice samples: the Enceladus Life Finder (ELF), proposed by JPL, and the Enceladus Life Signatures and Habitability (ELSAH), proposed by NASA Ames Research Center, the John Hopkins Applied Physics Laboratory, and NASA Goddard Space flight Center. The ELSAH mission achieved category 3 in the 2016 New Frontiers down selection and will receive technology development funding to develop cost-effective techniques to manage contamination enabling rigorous science to argue for the presence or absence of Life. In this context, NASA Ames Research Center (ARC) has been simulating plume fly-throughs of prototype collectors, collecting ice grains. During these impact tests, at the ARC's Vertical Gun Range (AVGR), basic side experiments involved the simultaneous measurement of microbial and biomarkers survival, and the monitoring/management of contamination levels of the prototype collectors (Section 3).

Planetary Protection Requirements for Ocean Worlds

Any mission to explore Ocean Worlds requires strict Planetary Protection Practices (PP) [e.g., 7-10] involve: (1) forward and reverse contamination of other planetary bodies, and (2) life detection false positives and negatives due to instrument contamination (see next section). Current COSPAR and NASA PP requirements of Category IV missions involve$<1x10^{-4}$ probability of contaminating an Ocean World with viable Earth microbes [11]. PP requirements to prevent forward contamination involve cleaning, sterilization or microbial reduction, and monitoring. Sterilization as well as bioburden monitoring of any payload component at direct contact with samples, such as a collector or a drill string are key aspects. So far, sterilization techniques for spacecrafts are more developed than bioburden monitoring ones [12]. Current life detection instruments target biomolecules rather then active microbial life. Thus, life detection, sample handling, and collecting devices require cleaning to reduce bioburden to less than the sensitivity of the instruments to ensure rigorous science data to validate or reject the presence of life (see next section). Very importantly, because fly-through sampling do not involve direct contact with planetary surfaces, or a plume's source, requirements for PP forward contamination are easier to be achieved by plume fly-throughs spacecrafts in comparison to landers.

A Key Life Detection Science Issue

A key issue for high sensitive life detection instruments for sample analysis, e.g., Capillary Electrophoresis instruments, Gas Chromatography mass Spectrometers, antibody microarray chips (in contrast to remote sensing instruments not at contact with the samples) is how to determine that a positive signal for a life biomarker is intrinsic to the measurement of the planetary body and not a result of exogenous contamination from Earth. In addition, the instrument detection sensitivity of any target organics must be aligned with the lower limit of the anticipated range of organics concentrations, in the target Ocean World, which may be very low, i.e., less than 80-120 cells/mL, which are the lowest values detected in Lake Vostok ice [e.g., 13], a relevant analog environment for icy shells. Thus, even low contamination levels in the life detection and collection devices may result in a contamination noise to signal ratio too high to provide a rigorous life/No life conclusion. The current state of the art protocols employ high cleaning standards to reduce the biomarker burden to less than the sensitivity of the instruments. Pre-launch techniques involve high oxidizing chemicals (e.g., vapor hydrogen peroxide and Ethanol), and exposure to ultraviolet or gamma rays. Post-launch practices involve the contribution of natural irradiation in space (≥10 Mrad) aiding in destroying biomarkers or altering their functionality. Another fundamental practice for contamination management involves the use of blank control samples just prior to receiving samples, to calibrate instrument against biomarker contamination. The contamination signal can be therefore subtracted from a positive signal detected from a planetary sample. However, it is difficult to run blanks in the case of sample collection/handling devices located in the very cold and vacuum space environment. Here, the bioburden is measured at the time of cleaning, prior to launch, instead of before receiving samples (possibly 10 years+ after launch). This is major science weakness for achieving life/No life conclusions.

2. Technical challenges

The following technical challenges are related to plume fly-through ice collectors, but they could also be applied to sample collection systems landed on the surface of an Ocean World.

How to determine contamination just before obtaining samples?

As described in the previous section, sample collection devices for plume fly-through missions are located in the cold hard vacuum space environment. Running blank control samples through a Collector prior to sample collection to measure contamination is very challenging compared to running blank control samples through instruments that are housed in a controlled environment. The issue needs resolving.

What are the cleanliness requirements of the surfaces?

The cleanliness requirements for the sample collection devices are not understood. Earth born biomolecules stuck to the walls of collectors may not be easily freed by incoming ice grains in the very cold outer solar system environment. The mechanisms that release these biomarkers and the quantity released needs to be understood and modeled.

What cleaning methods are adopted?

Finally, the most effective cleaning and bioburden monitoring methods need to be determined. Cleaning with an oxidizing gas in an oven has been considered but not tested. The measurement of contamination needs to be done without introducing more contamination.

3. Experiments of Contamination management for Fly-through sample Collection devices.

We describe here the current state of art and technology involving contamination management and Collector testing (done or in progress). These experiments involve: 1)

Microbial and biomarker impact survival tests where cleaning techniques were evaluated to minimize contamination [14], and 2) An experiment to determine the cleanliness requirement for a Collector using ^{13}C-glycine amino acid (in progress).

The NASA Ames Research Center (ARC) Vertical Gun Range (AVGR)

Experiments were conducted at the NASA ARC's Vertical Gun Range (Figure 1). Plumes of 140° K ice particles, travelling up to 2.3 Km/sec, were created by firing 3 mm hollow aluminum pellets (up to 6 Km/sec) at liquid nitrogen cooled ice pies inside the shooting chamber. Prototype Collectors (30° wall angled cone cross section) were positioned to catch the plume particles. 45 μm-sized particles were filmed in the process of impacting the cone inside wall and fragments funneled into a collection chamber located at the apex of the cone. Filters located in front of the Collector have been used to ensure ice grains are in the plume size range.

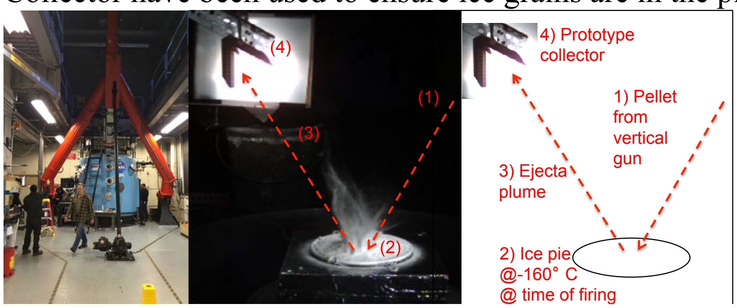

Figure 1: (Left) ARC Vertical Gun Range (AVGR). Center & Right: Collector and ice pie setup

1) Contamination mitigation during impact survival of microbial biomass and biomarkers.

The objectives of these experiments were to evaluate cleaning techniques applied to minimize contamination in the AVGR shooting chamber environment using an Adenosin triphosphate (ATP) Luminometry assay (Hygiena EnSURE). ATP is ubiquitous in life, does not survive after cellular death, and is a proxy for recent biological activity. The ATP assay is a non-culture based key technique of bioburden monitoring in spacecrafts [7-8, 15] and during field trials to monitor cross-contamination [16,17]. For the most recent VG experiments we used protocols that enabled mitigation of false negatives (kinetic-inhibited) and false positive (by reaction's enhancement), which are issues common to luminometric assays.

Contamination detection/mitigation practices

Collectors surfaces were wiped with Ethanol, sterilized in a Lysol bath overnight, followed by rinsing cycles with Zero Blank distilled water and flame sterilization. Processed surfaces were assayed with the ultrasensitive ATP surface swab (Limit of Detection: 0.2 10^{-15} moles (fmoles) of ATP). Positive and negative controls were run for each test. The degree of contamination present in the VG environment was monitored thru the experiments with three Blank shootings.

Mitigation practices involving Procedural Blanks allowed monitoring low to non-measurable bioburden during sampling of the target sea ice, or in the shooting chamber (Figure 2 below).

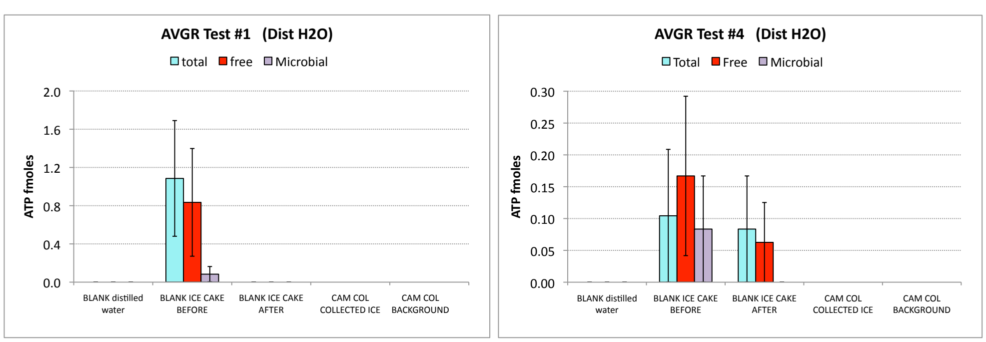

Figure 2. Left: Blank Contamination <2 fmoles/100uL monitored across experiments. Right: More strict aseptic practice ensured an even lower background ~0.3 fmoles ATP/100uL.

One issue related to life detection in briny samples concerned salt residues on the collector interfering with the ATP assay's chemistry and enhancing false negatives. Thus, false negative and positives could affect bioburden monitoring on spacecraft surfaces. On the journey to Enceladus or Europa, collector surfaces, if not covered with a biobarrier, will be potentially exposed to interstellar dust particles, organics, and salts. These exogenous compounds are not biological, but they can affect bioburden monitoring practices involving wet chemistry-based assays such ATP.

2) Determine the cleanliness requirement for a Collector using ^{13}C-glycine amino acid

The objective of this experiment is to determine the amount of contamination that is transferred from the inside Collector surface to an inner collector chamber. The result will enable determination of the Collector cleanliness requirement. The Ames vertical gun will be used to simulate a plume of icy particles impacting a Collector analogous to the Enceladus' plume. Before firing the AVGR, the cone wall is "artificially contaminated" with ^{13}C-glycine thin film in a deposition chamber. After deposition the thin-film depth is measured by a quartz crystal microbalance. After firing the AVGR, ^{13}C-glycine transferred into the cone apex container represents the amount of contamination collected. The collected sample with ^{13}C-glycine contamination is analyzed by Gas Chromatography-Mass Spectroscopy (GC-MS) to determine ^{13}C-glycine abundances compared to the ice collected. Thus an estimate of the ^{13}C-glycine feed from the surface by incoming ice grains can be calculated, leading to determining a cleanliness requirement for the Collector inside surface. The experiment is still in progress.

4. Conclusions/Recommendations

Our recommendations concern sample collection during plume fly-through missions but they are applicable for Ocean World Landers.

1. Planetary Protection (PP) forward contamination requirements can be met easier for plume fly-though spacecraft compared to landers.
2. PP requirements to mitigate forward contamination involve sterilization but current life detection instruments detect biomolecules. Thus, sample collection devices for life detection require cleaning and extensive bioburden monitoring. Contamination must be less than the sensitivity of the instruments.
3. A major weakness preventing rigorous science arguments for presence or absence of Life is the difficulty in running a blank control through collection devices before collecting samples.
4. Technical challenges include:
   a) How to determine the sample collector contamination just prior to obtaining samples?
   b) What are the cleanliness requirements of the Collector surfaces?
   c) What cleaning methods are adopted and how is cleanliness measured?

5 Contamination management recommendations:
   a) Effective bioburden monitoring practices will be required for Ocean Worlds.
   b) Bioburden management implemented at payload assembly and before sample collection.
   c) Mineral particles collected in space could affect bioburden monitoring leading to false negatives and positives. This is an overlooked issue and will require experimentation.

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SETI is Part of Astrobiology

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I. SETI is Part of Astrobiology

"Traditional SETI is not part of astrobiology" declares the NASA Astrobiology Strategy 2015 document (p. 150). This is incorrect.[1]

Astrobiology is the study of life in the universe, in particular its "origin, evolution, distribution, *and future* in the universe." [emphasis mine] Searches for *biosignatures* are searches for the results of interactions between life and its environment, and could be sensitive to even primitive life on other worlds. As such, these searches focus on the origin and evolution of life, using *past* life on Earth as a guide.

But some of the most obvious ways in which Earth is inhabited *today* are its *technosignatures* such as radio transmissions, alterations of its atmosphere by industrial pollutants, and probes throughout the Solar System. It seems clear that the *future* of life on Earth includes the development of ever more obvious technosignatures. Indeed, the NASA Astrobiology Strategy 2015 document acknowledges "the possibility" that such technosignatures exist, but erroneously declares them to be "not part of contemporary SETI," and mentions them only to declare that we should "be aware of the possibility" and to "be sure to include [technosignatures] as a possible kind of interpretation we should consider as we begin to get data on the exoplanets."

In other words, while speculation on the nature of biosignatures and the design of multi-billion dollar missions to find those signatures is consistent with NASA's vision for astrobiology, speculation on the nature of technosignatures and the design of observations to find them is not. The language of the strategy document implies NASA will, at best, tolerate its astrobiologists considering the possibility that anomalies discovered in the hunt for biosignatures might be of technological origin.

But there is no *a priori* reason to believe that biosignatures should be easier to detect than technosignatures—indeed, we have had the technology to detect strong extraterrestrial radio signals since the first radio SETI searchers were conducted in 1959, and today the scope of possibly detectable technosignatures is much larger than this. Furthermore, intelligent *spacefaring* life might spread throughout the Galaxy, and so be far more ubiquitous than new sites of abiogenesis. Life might be much easier to find than the NASA strategy assumes.

Indeed it has been cynically, but not untruthfully, noted that NASA eagerly spends *billions* of dollars to search for "stupid" life passively waiting to be found, but will spend almost nothing to look for the intelligent life that might, after all, be trying to

[1] Indeed, broad swaths of the astrobiology community disagree with NASA's assertion. For instance, SETI was included as a component of astrobiology in The Astrobiology Primer v.2.0 (Domagal-Goldman & Wright 2016), and SETI activities fall under the Carl Sagan Center for astrobiology at the SETI Institute (which, despite the name, conducts a broad range of science, including many sub-fields of astrobiology).

get our attention. This is especially strange since the discovery of *intelligent* life would be a much more profound and important scientific discovery than even, say, signs of photosynthesis on Ross 128*b.*

Further, since technosignatures might be both *obvious* and *obviously artificial* SETI also provides a shortcut to establishing that a purported sign of life is not a false positive, a major and pernicious problem in the hunt for biosignatures. SETI thus provides an alternative and possibly more viable path to the discovery of alien life than is reflected in NASA's astrobiology roadmap. Indeed, this was recognized explicitly in the panel reports of the Astro2010 decadal survey:

> *Of course, the most certain sign of extraterrestrial life would be a signal indicative of intelligence. [A radio] facility that devoted some time to the search for extraterrestrial intelligence would provide a valuable complement to the efforts suggested by the PSF report on this question. Detecting such a signal is certainly a long shot, but it may prove to be the only definitive evidence for extraterrestrial life.* (p.454, Panel Reports—New Worlds, New Horizons in Astronomy & Astrophysics)

II. Why is SETI Neglected in NASA's Astrobiology Portfolio?

While it is not completely clear *why* NASA does not include SETI in its astrobiology portfolio, there are several factors that seem likely to be at play.

The first is the risk of public censure: SETI sometimes suffers from a "giggle factor" that leads some to conflate it with "ufology" or campy science fiction. Indeed, such an attitude likely led to the cancelation of the last NASA SETI efforts in the early 1990's, after grandstanding by US senators denouncing "Martian hunting season at the taxpayer's expense" (Garber 1999). Such attitudes harm all of science, and the National Academies should be clear that such a "giggle factor" must not be allowed to influence US science priorities.

The second is the erroneous perception that SETI is an all-or-nothing proposition that yields no scientific progress unless and until it succeeds in detecting unambiguous signs of interstellar communication. On the contrary, even with scant funding, SETI has historically been involved in some of the most important discoveries in astrophysics. Not only have the demands of radio SETI led to breakthroughs in radio instrumentation (see, for instance, the new Breakthrough Listen backend at the Green Bank 100-meter telescope, with bandwidth of up to 10 GHz, an ideal Fast Radio Burst detection device; Gajjar et al. 2017), but some of the most famous SETI false positives have proven to be new classes of astrophysical phenomena, including active galactic nuclei (CTA-21 and CTA-102, Kardashev 1964), pulsars (originally, if somewhat facetiously, dubbed "LGM" for "Little Green Men"), and perhaps the still-not-fully-understood "Tabby's Star" (KIC 8462852, Boyajian et al. 2016, Wright et al. 2016, Wright & Sigurdsson 2017).

Indeed, exactly because SETI seeks signals of obviously artificial origin, it must deal with and examine the rare and poorly understood astrophysical phenomena that dominate its false positives. Anomalies discovered during searches for pulsed and continuous laser emission (Howard et al. 2007, Wright et al. 2014, Tellis & Marcy 2015, 2017) broadband radio signals, large artificial structures (Dyson 1960, Griffith et al. 2015, Wright et al. 2016), and other astrophysical exotica push astrophysics in new and unexpected directions. If there is a perception that SETI little more than the narrow search for strong radio carrier waves producing a long string of null results it is because historically there has been essentially no funding available for anything else.

Third, there is the erroneous perception that, since radio SETI as been active for decades, its failure to date means there is nothing to find. On the contrary, the lack of SETI funding means that only a tiny fraction of the search space open to radio SETI has been explored (Tarter et al. 2010). Indeed, Robert Gray has estimated that the total integration time on the location of the Wow! Signal (the most famous and credible SETI candidate signal to date) is less than 24 hours (see, for instance, Gray et al. 2002). That is, if there is a powerful, unambiguous beacon in that direction with a duty cycle of around one pulse per day, we would not have detected a second pulse yet. Other parts of the sky have even less coverage. The truth is, we only begun to seriously survey the sky even for radio beacons, and other search methods have even less completeness.

Fourth, there is the erroneous perception that SETI will proceed on its own without NASA support. Indeed, the 2015 NASA Astrobiology Roadmap claims that "traditional SETI is…currently well-funded by private sources." Even setting aside the non sequitur of considering the amount of private philanthropic funding when assessing the merits of the components of astrobiology, this is not a fair description of the state of the field. While it is true that the Breakthrough Listen Initiative has pledged to spend up to $100 million over 10 years, in truth its spending has been far below that level, and it is focused on a small number of mature search technologies. Beyond this initiative, private benefactors have supported the SETI Institute's Allen Telescope Array, but not at the level necessary to complete the array or fund its operations.

Fifth, there is the erroneous perception that the search for technosignatures is somehow a more speculative or risky endeavor than the search for biosignatures. We note that the entire field of astrobiology once faced a similar stigma. Chyba & Hand rebutted that perception in 2005:

> *Astro-physicists...spent decades studying and searching for black holes before accumulating today's compelling evidence that they exist. The same can be said for the search for room-temperature superconductors, proton decay, violations of special relativity, or for that matter the Higgs boson. Indeed, much of the most important and exciting research in astronomy and physics is concerned exactly with the study of objects or phenomena whose existence has not been demonstrated—and that may, in fact, turn out not to exist. In this sense astrobiology merely confronts what is a familiar, even commonplace situation in many of its sister sciences.*

Their rebuttal holds just as well as SETI today. Indeed, Wright & Oman-Reagan (2017) have articulated a detailed analogy between SETI and the relatively uncontroversial search for dark matter particles via direct detection. They argue that unlike with dark matter searches, with SETI, at least, we have the advantage that we *know* that the targets of our search (spacefaring technological species) arise naturally (because we are one).

Finally, there is an erroneous perception that SETI is exclusively a ground-based radio telescope project with little for NASA to offer. On the contrary, SETI is an interdisciplinary field (Cabrol 2016) and even beyond the potential for NASA's Deep Space Network to play an important role in the radio component of SETI, archival data from NASA assets have played an important role in SETI for decades: from Solar System SETI using interplanetary cameras, to waste heat searches using *IRAS* (Carrigan 2009) *WISE, Spitzer,* and *GALEX* (Griffith et al. 2015), to searches for artifacts with *Kepler* (Wright et al. 2016) and *Swift* (Meng et al. 2017). Future ground-based projects like LSST and space-borne projects like *JWST* and *WFIRST* will undoubtably provide additional opportunities SETI research both as ancillary output of legacy and archival programs and through independent SETI projects in their own right.

III. Reinvigorating SETI as a Subfield of Astrobiology

One difficulty SETI faces is a negative feedback between funding and advocacy.

As it stands, SETI is essentially shut out of NASA funding. SETI is not mentioned at all in most NASA proposal solicitations, making any SETI proposal submitted to such a call unlikely to satisfy the merit review criteria. Worse, **the only mentions of SETI in the entire 2015, 2016, and 2017 ROSES announcements are under "exclusions,"** in the Exobiology section ("Proposals aimed at identification and characterization of signals and/or properties of extrasolar planets that may harbor intelligent life are not solicited at this time") and the Exoplanets section (as "not within the scope of this program.") In other words, SETI is ignored entirely in NASA proposal solicitations, *except for those most relevant to it*, in which cases it is *explicitly excluded*.

Meanwhile, other parts of astrobiology have flourished under NASA's aegis, which has incubated strategies for the detection of life elsewhere in the universe, and produced scientists who can advocate for mature roadmaps to the detection of life in the universe as part of NASA's astrobiology program. But now, twenty years after the last major NASA SETI program was cancelled, there are only a handful of SETI practitioners and virtually no pipeline to train more.

Thus there are only a few well-developed strategies to advocate for, and only a few scientists to advocate for them. This will doubtless be reflected in the number of white papers advocating SETI (like this one) versus those advocating other kinds of astrobiology responsive to the current call. This disparity should not be seen as indicating a lack of intrinsic merit of the endeavor of SETI, but as a sign of neglect of SETI by national funding agencies.

Since SETI is, quite obviously, part of astrobiology, SETI practitioners should at the very least be *expressly encouraged* to compete on a level playing field with practitioners other subfields for NASA astrobiology resources.

Doing so will uncork pent-up SETI efforts that will result in significant progress over the next 10 years and beyond. As a fully recognized and funded component of astrobiology, SETI practitioners will be able to develop new search strategies, discover new astrophysical phenomena and, critically, train a new generation of SETI researchers to guide NASA's astrobiology portfolio to vigorously pursue the discovery of all kinds of life in the universe—both "stupid" *and* intelligent.

And if, as many suspect, technosignatures prove to be closer to our grasp than biosignatures, then including of SETI in NASA's astrobiology portfolio will ultimately lead to one of the most profound discoveries in human history, and a reinvigoration of and relevance for NASA not seen since the Apollo era. In retrospect, we will wonder why we were so reluctant to succeed.

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