Astrobiology at APL—On the Path to Discovery

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ABSTRACT

Astrobiology is an exciting field of science focused on understanding the origins, evolution, distribution, and future of life in the universe. NASA focuses much of its research and technology developments on astrobiology, and the Johns Hopkins University Applied Physics Laboratory (APL) is a major contributor through research, technology, and missions. Astrobiology efforts at APL range from constraining when life first emerged on Earth and researching biosignature (i.e., signals of past or present life) preservation, to developing instruments and missions aiming to detect biosignatures and characterize the capability of an extreme planetary environment to harbor and support life. Beginning with APL's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter (MRO), which searches for past wet and potentially habitable regions on Mars, APL has continued to develop cutting-edge techniques and instruments to search for biosignatures, remotely and in situ. Additionally, APL is leading and serving as a key partner in several exciting NASA missions that will occur in the coming decades with habitability and biosignature detection goals. In this article, we summarize current efforts and look forward, over the coming 25 years, to the potential astrobiology exploration and discoveries that await.

INTRODUCTION

The Johns Hopkins University Applied Physics Laboratory is conducting wide-ranging research and developing numerous missions and instruments related to astrobiology and the habitability of worlds in our solar system and beyond. APL's first foray into astrobiology began in 2001 when NASA competitively selected the APL-led instrument, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM),[1] for flight on the Mars Reconnaissance Orbiter (MRO).[2] MRO's objectives include finding sites on Mars that may preserve a record of past wet environments, enabling researchers to assess whether any of these environments might have been habitable. CRISM's observations have informed landing site selections for in situ instrumentation investigations for biosignatures, including NASA's Mars Science Laboratory and Mars 2020 missions.

Additionally, building on the discovery that communities of chemosynthetic organisms can live in hydrothermal vents at Earth's seafloor,[3,4] APL is considering the habitability of ice-covered ocean worlds through laboratory and field studies, instrument developments, and missions to Europa, Enceladus, Titan and the moons of Uranus and Neptune. These cutting-edge efforts will interrogate the habitability of distant worlds and attempt to detect biosignatures and extraterrestrial life, through both remote and in situ observations. Further, as researchers begin to grasp greater detail on exoplanets, APL's investigations will help to constrain where habitable worlds may exist, whether their atmospheres indicate signs of life, and to what extent they may support life. It is an exciting time as astrobiology research strengthens as a main priority of NASA's strategic plan. The community can count on key contributions from APL now and in the future.

MODELING, LABORATORY, AND FIELD STUDIES

Research at APL is the backbone of both understanding our universe and driving mission objectives and instrument development. Several innovative astrobiology investigations are underway, ranging from those that provide context to when life originated in our solar system, to those that seek to understand the ability of various extreme environments to harbor life, to those that explore the potential of these environments to preserve signatures of past life. In addition to conducting laboratory and modeling studies, researchers at APL perform in situ studies of biology and its ecosystems. Increasing understanding of how Earth life sustains itself in harsh, nutrient-poor, transient conditions is critical to understanding how life may exist in similarly challenging planetary environments. Each study will produce new science results that drive mission objectives and technology developments to improve our ability to know where and how best to look for life at other worlds.

Characterizing Nearby M Dwarf Habitable Zone Planets

Identifying habitable (and possibly inhabited, by extant life forms) planets around other stars is one of NASA's greatest long-term goals. Significant resources have gone into first finding these planets, with great success. Ground-based surveys, the Kepler/K2 missions, and TESS (Transiting Exoplanet Survey Satellite) have found more than 1,000 terrestrial exoplanets. Of these worlds, the most scientifically compelling targets in the search for extrasolar life are known to orbit M dwarf stars, which are cooler and smaller than our Sun. They are also the most numerous stars in the galaxy, accounting for 75% of our closest neighbors. Systems such as Proxima Centauri, TRAPPIST-1, and LHS 1140 represent our best (and only) opportunity this decade to investigate the prevalence of life in the solar neighborhood. This is because only those habitable worlds that orbit M dwarfs are large enough relative to the parent star to yield detectable atmospheric molecular signatures.

With the forthcoming launch of the James Webb Space Telescope (JWST), and soon-to-be commissioned ground-based extremely large telescopes, detailed atmospheric observations of terrestrial worlds orbiting M dwarfs are imminent. However, it remains to be seen whether we will have the comprehensive modeling framework necessary to correctly interpret the results and avoid making premature claims of detecting signs of life. A new APL-led program intends to guard against errant interpretations by addressing one of the most pressing exoplanet science questions in the era of JWST: Can M dwarf planets support life, and if so, how do we best observe and characterize them? Dr. Kevin Stevenson is leading a multi-institutional team of two dozen experts to develop the comprehensive modeling framework needed to accurately assess the habitability of terrestrial planets in or near the habitable zones of M dwarf stars and utilize these insights to develop requirements for a future space-based survey mission whose goal is to constrain the fraction of rocky worlds that develop life.[5]

Crater Dating to Inform Impactor Activity Near Time of Origin of Life on Earth

While it might seem counterintuitive, Earth's Moon is of great importance in addressing the mystery of how and when life began on Earth. Both Earth and the Moon were heavily bombarded with giant, basin-forming impactors around 4 billion years ago—the very time frame in which our earliest evidence indicates life emerged on Earth. Earth's geologic record from this era of basin-forming impacts has been largely destroyed by active geology, hydrology, and biology. Yet, the preserved giant basins on the Moon faithfully record the timing of the flux of impactors. Establishing the timing and duration of large basin formation for the Moon requires lunar surface missions to sample and measure these basins' radiometric ages from carefully selected impact melt deposits around the Moon. This crucial record serves as a proxy record for Earth and informs us on the impactor environment that the earliest life-forms survived or emerged from later. Understanding this environmental record on the Moon and Earth is a piece of the puzzle for deciphering that mysterious transition from geochemistry to biochemistry. Dr. Kirby Runyon et al.[6] began to address this issue in a recent study.

The Venus Life Equation

Ancient Venus and Earth may have been similar in crucial ways for the development of life, such as having liquid water oceans, land–ocean interfaces, favorable chemical ingredients, and energy pathways. If life ever developed on, or was transported to, early Venus from elsewhere, it might have thrived, expanded, and then survived the changes that have led to an inhospitable surface on Venus today. The Venus cloud layer may provide a refugium for extant life that persisted from an earlier more habitable surface environment. Dr. Noam Izenberg and coauthors from multiple research institutions recently introduced the Venus Life Equation[7]—a theory and evidence-based approach to calculate the probability of extant life on Venus, *L*, using three primary factors of life: origination, robustness, and continuity, or $L = O \bullet R \bullet C$. They evaluated each of these factors using our current understanding of Earth and Venus environmental conditions from the Archean era, more than 2.5 billion years ago, to the present. They found that the probability of origination of life on Venus would be similar to that of the Earth and argue that the other factors should be nonzero, comparable to other promising astrobiological targets in the solar system. The Venus Life Equation also identifies poorly understood aspects of Venus that can be addressed by direct observations with future exploration missions.

Earth 2.0

APL leadership often solicits innovative project ideas to foster collaboration and growth of new expertise across the Lab's sectors. One such project sought to find technical solutions to moderate extreme environments and increase the number of planetary habitats that can sustain humans. Earth 2.0, led by APL researcher Leif Powers, investigated the feasibility of using a biofilm to perform novel chemical processing on other planets. Biofilms are already used on Earth—for example, in wastewater treatment, where they usually consist of an ensemble of existing Earth organisms that feed on the waste. The APL Earth 2.0 team worked to construct a biofilm capable of capturing mission-relevant amounts of energy while growing on a Mars- or Venus-like regolith, so that it could conduct critical chemical processing. With time, the biofilm could spread and its consumption of feedstocks, such as carbon dioxide, would result in a more habitable environment for humans and Earth life.

The primary challenge to any biological terraforming concept is bioavailable energy. The next steps, beyond the current scope of APL's biofilm effort, would be to create a new baseline for life tuned to specific planetary bodies in order to sustain the environment-changing biology. One approach to that baseline would be genetic engineering to produce more durable secretions in the extracellular matrix that could mitigate radiation bombardment, temperature extremes, and atmospheric insults. These life-forms would need to substitute elements such as increased metal content during their life cycles to compensate for elemental availability and climate baselines. Changing the environments of whole planets would not be trivial, yet studies such as those being conducted at APL could potentially make the process possible. Our understanding of the adaptability of life as we know it would also be transformed.

Habitability of Dunes as Mars and Titan Analogs

Despite extreme temperature swings and paucity of water, desert soils host diverse and active microbial communities that are distinct from other biome soils. Microbes are also found in the top layer of sand dunes, but the habitability of the more benign dune interior has yet to be explored. The unique environmental conditions there include increased structure, increased moisture, moderated temperature variation, and greater protection from ultraviolet (UV) radiation relative to the surface soil. Understanding the link between the environment and the inhabitants in terrestrial dunes is critical for evaluating the habitability potential of dunes elsewhere in the solar system, especially Mars and Titan, where surface conditions are even more extreme than on Earth. Scientists at APL including Dr. Shannon MacKenzie, in partnership with the University of Maryland Institute for Genome Sciences and Brigham Young University, are conducting in situ investigations at terrestrial dunes to concurrently quantify physical, chemical, and biological characteristics. Comparing these data will provide fundamental new insight into processes and conditions that create and maintain habitable environments, thereby informing the search for such environments beyond Earth.

Preservation of Microbial Biosignatures in Hot Spring Deposits, with Applications to Mars Exploration

The deposits of silica-precipitating hot springs on Earth have long been identified in rocks dating as far back as the Archean era more than 2.5 billion years ago,[8,9] indicating the existence of habitable environments early in Earth's history. The discoveries of silica-rich deposits by the Mars Exploration Rover Spirit in Gusev Crater, and by the CRISM instrument on MRO at other locations on Mars,[10,11] provide evidence of potential past hot spring environments on Mars that may have also been favorable for microbial life and biosignature capture and preservation.[12,13] The long-term preservation of biosignatures in ancient rocks is strongly correlated with the depositional environment, rock type(s), and subsequent geologic history (i.e., burial, diagenesis, or degree of metamorphism). While diagenetic alteration may modify primary biological textures, and organic remains can be obliterated by recrystallization,[14–16] biosignatures can still be preserved over eons.[8,9] APL researcher Dr. Jorge Núñez investigated Miocene-age (5–23 million year old) siliceous sinter deposits from the Coromandel Peninsula on North Island, New Zealand,[17] comparing them to modern silica hot spring deposits in Yellowstone National Park and the Taupo Volcanic Zone in New Zealand to better understand processes of biosignature capture and preservation and how post-depositional changes ("diagenesis") affect microtexture, composition, and biosignature retention. These types of deposits are considered analogs to similar deposits on Mars.[12]

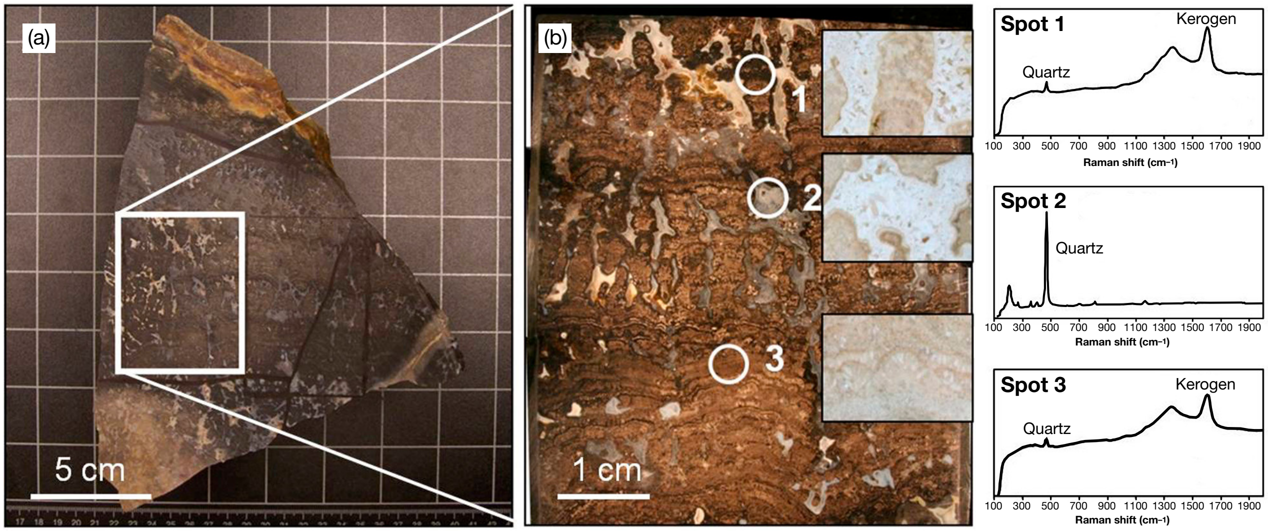

Figure 1. (a) Example of Miocene-age siliceous sinter from Otama Beach (Coromandel Peninsula, New Zealand) with (b) palisade microfacies. The deposits have undergone diagenetic recrystallization and cementation of porous fabric to quartz and corresponding spectra of laser Raman spot analysis (spots 1–3 labeled with white circles, and spectra at right). The insets in panel b are thin section views (20× magnification) of the circled areas. Spots 1 and 3 correspond to the palisade layer, while spot 2 corresponds to quartz-filled vug with Raman peaks for spots 1 and 3, consistent with kerogen. The Raman spot size is 10 µm.

Study results showed that the Miocene-age sinters have experienced significant overprinting of primary textures by early diagenetic cementation of the originally porous sinter framework and recrystallization of opaline silica to quartz. Despite extensive recrystallization, primary depositional textures and other bioindicators (e.g., biofabrics, plant remains, microbial filaments, and disordered carbonaceous material—i.e., kerogen) are preserved, especially in cooler distal pool microfacies. For example, in Miocene samples from Otama Beach (Coromandel Peninsula, New Zealand), microbial palisade fabrics (Figure 1) are well preserved. When analyzed with laser Raman spectroscopy (spots 1 and 3 in Figure 1), organic signatures (kerogen) were shown to be present by Raman peaks centered at 1,350 and 1,605 cm^{-1}. Detection of these signatures indicates the potential that such biosignatures could also be preserved at Mars.

These results also emphasize the scientific utility of nondestructive techniques, such as microspectroscopy and laser Raman spectroscopy, while microscale mapping of primary and secondary phases reveals paragenetic relationships and links mineralogy to the microtextural framework of the rock.[17] These techniques enable more precise petrogenetic interpretations, provide a context for inferring microscale variability and habitability, focus the search for fossil biosignatures, and provide additional constraints for evaluating the biogenicity of suspect biosignatures. Future studies will investigate the preservation potential of microbial biosignatures, in particular organic biosignatures, along thermal gradients to better focus future sampling strategies of similar deposits on Mars.

Habitability of an Ancient Hellas Basin Martian Environment

Dr. Christina Viviano is investigating the habitability of a unique ancient environment at the rim of the Hellas impact basin on Mars within its surrounding ring of uplifted massifs.[18] This is a unique region where long-lived elevated temperatures and fluid circulation via fracturing may have sustained a habitable environment in the near-surface. Dr. Viviano will use the High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) images to map fractures and dikes to characterize the geomorphologic signatures of the uplifted massifs, will use CRISM data to compositionally map the distribution of alteration minerals associated with the massifs, and will analyze the correlation between fractures and dikes with mineralogy. Her colleague Dr. James Roberts will perform numerical modeling of the upper 1 km of the surface, subsequent to the Hellas impact, to help constrain the timing and stability of mineral formation, thus characterizing the potential habitability of the environment.

Preservation of Organics in Icelandic Hydrothermal Sinter Deposits

To investigate a potential subsurface biosphere on Mars, as postulated by Michalski et al.,[19] researchers should select sites where crustal uplifts or hydrothermal activity brought fluids to the surface. The Nili Patera caldera in the Syrtis Major volcanic province exhibits mound morphology and silicic sinter deposits indicating past hydrothermal activity[20] and conditions for a

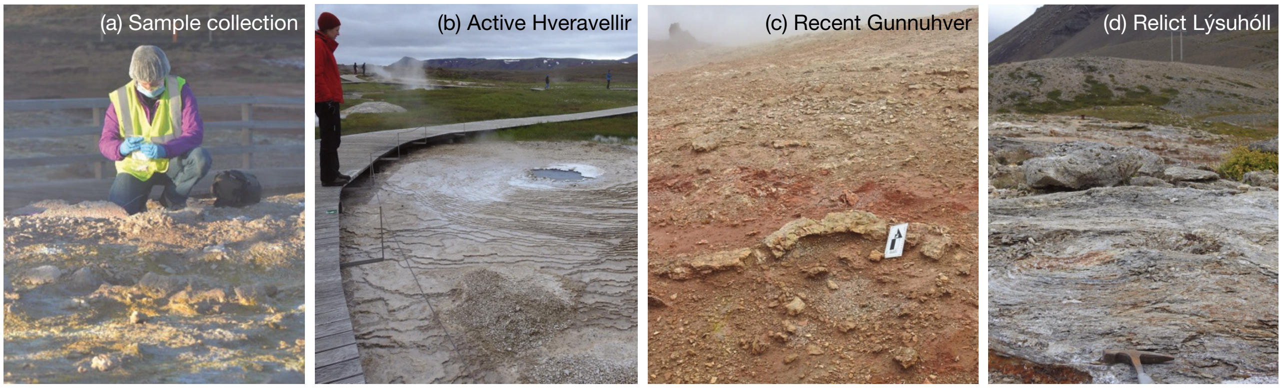

Figure 2. Samples collected during the NASA Planetary Science and Technology Through Analog Research (PSTAR) Seeking Signs of Life in Nili Patera (SSLNP) project (principal investigator, J. R. Skok). (a) Dr. Craft collecting samples. (b–d) Sampled sinter sites in Iceland of various activity levels.

habitable conduit from the potential deep biosphere to the surface. These sinters provide ideal locations to concentrate and preserve potential biosignatures that could be targets for future planetary exploration. Dr. Kate Craft of APL, participating in a NASA Planetary Science and Technology Through Analog Research (PSTAR) project called Seeking Signs of Life in Nili Patera (SSLNP) led by Dr. J. R. Skok of the SETI Institute, traveled to three hydrothermal sinter sites in Iceland during the summer of 2016 to explore analog sinter sites and biosignature preservation. While there, Dr. Craft and fellow team members employed several exploration methodologies, including spectroscopic, mineralogic, microscopic, molecular, and geophysical techniques, to investigate the biological, environmental, and volcanic history of the analog sites. Dr. Craft collected organically clean samples at three sinter sites at the surface and at subsurface depths of ~6–8 cm, and at near-vent, mid-apron and distal apron locations, to determine whether molecular biosignatures, such as lipids, are (1) preserved in the sinter and (2) detectable with a benchtop version of the TMAH (tetramethylammonium hydroxide) wet chemistry experiment on the SAM (Sample Analysis at Mars) instrument on the Curiosity rover (Figure 2). Site activity ranged from currently active to relict, with results revealing loss of monounsaturated fatty acids at depth, indicative of early diagenesis.[21] The team also observed that saturated fatty acid methyl esters with odd carbon numbers were lost at depth, while those with even carbon numbers were preserved. These results indicate that fatty acids are preserved at depth at the modern and relic Icelandic sinter sites and are detectable with a benchtop version of the SAM TMAH wet chemistry experiment. These results also suggest that sinter sites at Mars may harbor evidence of life if it was ever brought to the surface through a similar hydrothermally driven spring system.

PROPOSED RESEARCH

Proliferate—Earth 2.0 Propulsion Grant Proposal

An APL team proposed the Proliferate concept as part of APL's Propulsion Grant cycle. (See the article by Kedia and Krill, in this issue, for more on APL's grant programs.) Its goal is to rapidly modify an environment to support life by developing enabling technologies to install a plant-based carbon cycle on a Mars-like planet. The intent of the effort would be to develop technologies to recreate a terrestrial carbon cycle in a Mars-like environment driven by plant growth, with the goal of starting from current Mars conditions and ending with a self-sustaining ecosystem. The concept includes an ecosystem engineering approach driven by mechanistic models describing the interplay between biological and environmental processes.

Engineering the Plant Microbiome for Growth under Stressors of the Spaceflight Environment

The ability to grow plants in the spaceflight environment represents a source of fresh food and an opportunity to improve air quality. Elevated CO_2, pathogen susceptibility, high humidity, microgravity, increased radiation levels, and hydroponic growth are some of the conditions that impact plant growth and health in the spaceflight environment. In terrestrial systems, the plant microbiome has been shown to alleviate or partially suppress negative growth effects from some abiotic stressors or pathogen infection. A team led by Dr. Collin Timm is proposing to investigate how elevated CO_2 modifies plant molecular and physiological response and identify microbial communities that reduce plant stress from high-CO_2 environments. This work will also provide information on plant–microbiome relationships that will facilitate environment modification (e.g., terraforming Mars).

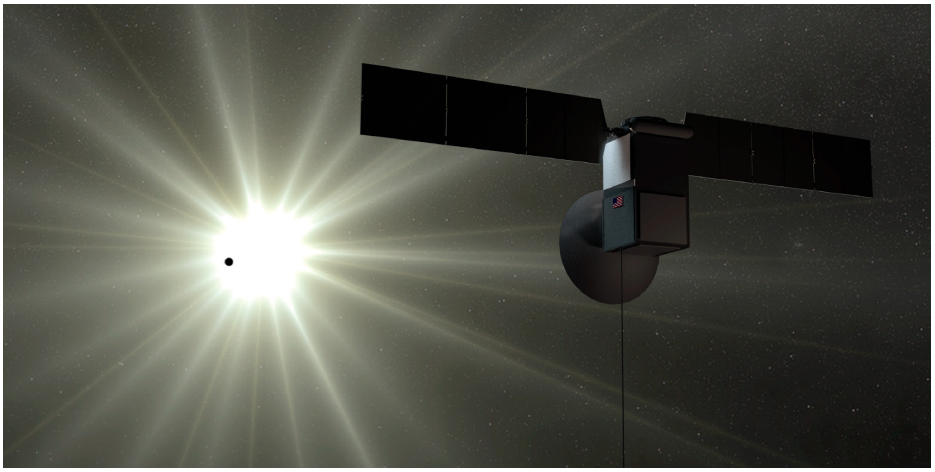

Figure 3. Artist's concept of the Star Helix mission that would send a spectrometer past the Earth–Sun Lagrange 2 point to observe transits of the Earth across the Sun and validate the methods astronomers intend to use with next-generation space telescopes, like the JWST, for detection of possibly habitable worlds. (Image credit: APL, Xplore, and Bryan Versteeg/Spacehabs.com.)

Star Helix

If we observed Earth the same way we plan to observe potentially Earth-like exoplanets, would we be able to detect, through spectral indicators in the atmosphere, that it is habitable, or that it is currently inhabited by existing life? These are the questions that the proposed Star Helix Astrophysics Pioneers mission would seek to answer by sending a spectrometer past the Earth–Sun Lagrange 2 point to observe transits of the Earth across the Sun (Figure 3). These observations are very similar to telescopic observations of exoplanets transiting around their host stars. A key science objective of the Star Helix mission is to validate the methods astronomers intend to use with next-generation space telescopes, like the JWST, for characterizing possibly habitable worlds during transits of their parent stars. The Star Helix team, led by Dr. Noam Izenberg and Dr. Kevin Stevenson, would observe multiple Earth transits, coupled with independent knowledge of contemporaneous solar activity and terrestrial conditions, to extract time-varying spectra of the Earth's atmosphere, and look to discriminate key atmospheric species that indicate the Earth is habitable—or even that it has life on it today. This methodology test is critical for the future of exo-astrobiology.

INSTRUMENT DEVELOPMENTS

Future planetary missions seeking signs of life and determining habitability will need instruments that can maximize scientific return but maintain low size, weight, and power (SWaP) so they can be accommodated on resource-constrained spacecraft, landers, and mobile platforms such as rovers, copters, and cryobots. APL is developing several instruments that can search for signs of life and also provide important contextual information to inform analyses, choice of sampling sites, and understand a detection or nondetection in a particular sample.

The Advanced Multispectral Infrared Microimager

Microscopic imaging has long been an essential tool for field geologists and in the robotic exploration of planetary surfaces. Microscale texture and mineralogy are essential for properly identifying rocks and soils in situ and interpreting their geologic histories. Over the past decade, the microscopic imagers on the Mars Exploration Rovers,[22] the Phoenix lander,[23] and the Mars Science Laboratory[24] have played such critical roles in those missions that microscopic imagers are recognized as essential tools for landed planetary missions.[25–27] While these microscopic imagers have provided valuable microtextural information, they lack the ability to robustly discriminate mineralogy, essential for assessing petrogenesis.

Combining microscopic imaging with visible/near-infrared (VISIR) reflectance spectroscopy provides a powerful in situ approach for obtaining mineralogy within a microtextural context. The approach

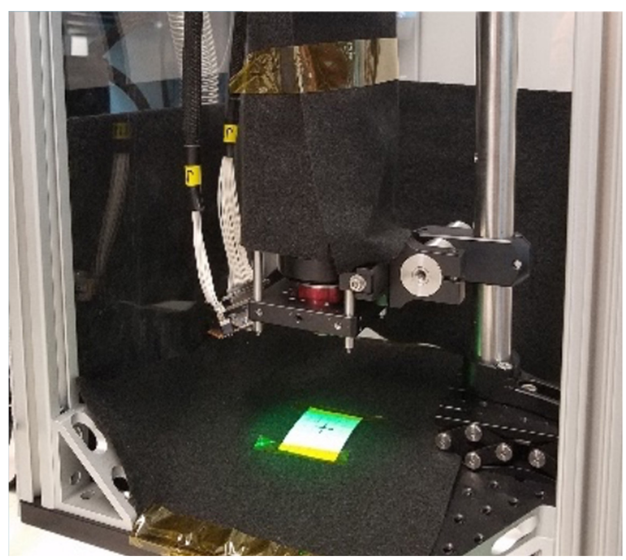

Figure 4. Prototype version of the Advanced Multispectral Infrared Microimager (AMIM) instrument. The instrument is shown with green (525 nm) LEDs turned on.

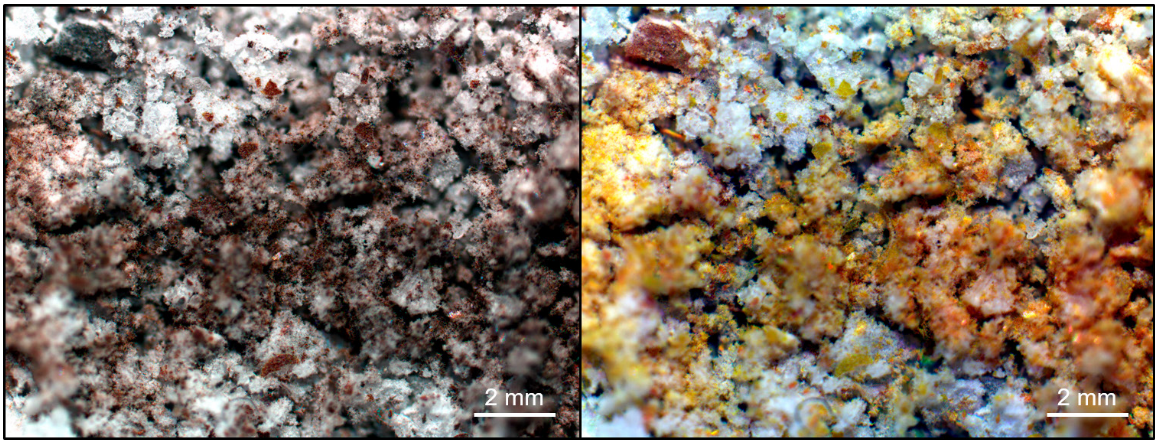

Figure 5. A sample viewed by AMIM. Shown is a tholin-water ice mixture, applicable to ocean worlds such as Saturn's moon Titan, illuminated with AMIM's LED bands R = 630 nm, G = 525 nm, B = 455 nm (left) and R = 935 nm, G = 770 nm, B = 455 nm (right), respectively. The image field of view is 14.1 mm × 10.5 mm with a spatial resolution of 6 µm/pixel. The two tholin samples, each made with 5% and 10% methane, respectively, while indistinguishable in the visible (left), are clearly distinguishable in the false-color image (right), with orange and yellow colors, respectively. (Tholin samples credit: Dr. Sarah Hörst, Johns Hopkins University.)

is nondestructive and requires minimal mechanical sample preparation. Dr. Jorge Núñez and team at APL developed the Advanced Multispectral Infrared Microimager (AMIM) (Figure 4) for future planetary missions to provide in situ, spatially correlated mineralogical and microtextural information on rocks and soils at the microscale. This information will support traverse characterization and geologic mapping, prospecting for resources, identifying potential biosignatures, and facilitating the selection of samples for onboard analysis with other instruments.[28]

AMIM consists of compact, low-power multispectral LED arrays coated with narrow-bandpass filters (>20 wavelengths with full width at half-maximum ≤50 nm), an adjustable focus mechanism capable of focusing from a distance of few centimeters (spatial resolution ≤ 30 µm/pixel) to infinity with a high depth of field, and an infrared camera capable of imaging from the VISIR to the shortwave-infrared (nominally 0.4–2.6 µm).[29] This wavelength coverage has wide applicability for the detection of minerals and ices along with potential biosignatures (e.g., Figure 5). However, specific wavelengths and spectral range (up to 4 µm) can be easily tailored to address specific mission science and engineering requirements. AMIM's design eliminates the need for complex optics, scanning mechanisms, or electronically tunable filters, thereby reducing instrument complexity and SWaP, enabling AMIM to be deployed on a small robotic arm or body of a small lander or rover. Furthermore, AMIM provides flexibility by allowing data to be collected at a variety of distances under a variety of illumination conditions. Thus, AMIM would provide many of the capabilities commonly associated with orbital instruments such as CRISM[1] on MRO[2] or the Moon Mineralogy Mapper (M^3) on Chandrayaan-1,[30] but at a size and mass comparable to current microscopic imagers for landed science—a capability unmatched by any current microimaging instrument developed for flight.

In Situ Devices for Biosignature Purification and Analyses

Whether exploring one of the icy ocean worlds including Titan, Europa, Enceladus, or others, the clouds of Venus, or the rocky subsurface on Mars, searching for life in these environments presents a number of challenges. One major challenge is that planetary samples are likely chemically complex, with high salinity, and are expected to have very low biomass, if present. These environmental factors can confound the instruments/techniques currently used to analyze in situ samples for biosignatures, making sample preparation capabilities and instrument design critical. In addition to sample complexity, the search for life in space relies on the use of miniaturized precise analytical equipment that can detect key biosignatures—amino acids, fatty acids, proteins, long-chained biopolymers (e.g., DNA-like), etc.—on low-SWaP, automated platforms that can sustain long-duration flights and operate in high-radiation environments. Currently, systems for fluid processing in flight are few. To fill this need, a focus at APL is on development of capable, in situ sample preparation and analyses instruments to detect biosignatures at extraterrestrial worlds.

Amino Acid Sample Preparation

One solution being developed at APL for amino acid purification and enrichment, in an effort being led by Dr. Kate Craft and Dr. Christopher Bradburne, is a millifluidic sample preparation technique capable of purifying and desalinating proteinogenic amino acids, independent of the pH, salinity, and type of salt in the sample.[31,32] This device can be used in situ as a single purification tool for multiple downstream biosignature detection analyses techniques. The ion exchange technique used for the purification follows similar methods developed for desalinating meteorite samples on Earth for example;[33] however, it has yet to be developed as an automated, in situ flight instrument that is robust to environmental factors and a range of planetary chemistries. APL sample purifications have been performed successfully for control samples containing phenylalanine and three analog salt types, NaCl, $CaCl_2$, and $MgSO_4$, producing varying capture yields. These results indicate that there is some competition of the Ca^{2+} cation with the amino acid for binding sites. Increasing the bead bed size or running the sample through a second bead bed can be planned as a mitigation for environments having a high Ca^{2+} content to maximize amino acid capture. Work continues to develop this purification technique and integrate it with front-end sample handling and delivery.

Sample Preparation and Characterization for Long-Chained Polymers

Dr. Kate Craft and Dr. Christopher Bradburne are leading another effort to develop and optimize miniaturized on-chip devices to disrupt, purify, and characterize long-chained polymers (LCP)—for example, DNA- and RNA-type molecules.[34] Sample preparation techniques are being employed on a microfluidic chip for delivery to a downstream nanopore sequencing platform. This device will streamline the purification and preparation of planetary samples in situ, on a platform conducive to flight, and enhance the signal-to-noise ratio for downstream analyses. Characterization of LCPs would also be useful for identification of terrestrial contamination, if present. The team is also developing a synthetic nanopore device capable of operating in the harsh conditions of space.[35] An additional high hurdle for flight operation of such an instrument is the high volume of data that a sequencer could return. APL researchers are developing bioinformatic techniques to triage, onboard, the extremely large data sets. With a robust sample-to-answer device to purify and detect LCPs, planetary missions will be able to interrogate complex samples for signs of life on a miniaturized platform, even if the samples have extremely low biomass.

Astrobiological Molecularly Imprinted Polymer Sensors

From 2003 to 2010, Dr. Noam Izenberg, Dr. Kelly Van Houten, and a number of other contributing APL scientists conducted an internally funded pilot and then NASA Astrobiology Science, Technology and Instrument Development program (ASTID)-funded research to develop molecularly imprinted polymers (MIPs) for detection of astrobiologically relevant molecules. The purpose of the Astrobiological MIP Sensor (AMS) project was to develop reliable, low-cost, low-weight, low-power consumption detection technologies for in situ analysis of biochemical markers and other indicators of astrobiological importance.[36] To this end, the team investigated the potential role that MIPs could serve in the recognition of prebiotic and biotic compounds in planetary, astrobiological, and geochemical mission profiles. While MIPs are effective molecular recognition tools, a signal transduction method must be developed so that the recognition of analytes can be realized. The study produced a method for creating water-soluble MIPs that helped advance their utility for future sensor development.[37]

Sample Handling and Preparation

Under NASA development funding, APL researchers, led by Dr. Mark Perry, have teamed with SwRI (principal investigator, Dr. Chris Glein) to develop an instrument that can detect the molecular precursors of life and can search for evidence of life.[38] The revolutionary ORganic Compositional Analyzer (ORCA) is composed of (1) a microfluidic sample handling and preparation system developed by APL, (2) a novel micro-device gas chromatograph developed by the University of Michigan, and (3) a mass spectrometer based on the Europa Clipper MASPEX built by SwRI. The handling and preparation system being developed at APL warms the ice sample and delivers gases and liquids to the rest of the instrument subsystems for purification, enrichment, and analysis. ORCA will have exceptional capabilities to search for organic signatures of life, to enable assessments of the chemistry of the environments of ice-rich bodies such as Europa or Enceladus, and to measure molecular indicators of habitable conditions.

Europa Lander Stereo Spectral Imaging Experiment

Another instrument under development at APL and funded by NASA is the Europa Lander Stereo Spectral Imaging Experiment (ELSSIE), led by principal investigator Dr. Scott Murchie.[39] The instrument would address a major challenge for a Europa lander, providing the imaging and spectral data needed to decide which spots among several square meters of accessible surface area are accessible, safe to sample, and most likely to contain materials of scientific interest. ELSSIE takes a lesson from CRISM in that a carefully selected subset of spectral channels can accomplish most of the science, but full spectral sampling is optimal for targets of interest. ELSSIE's design makes the instrument look like a cyclops: left and right camera "eyes" take stereo images at selected visible and infrared wavelengths that indicate the presence of organic materials, ocean salts, or fresh ice in which trapped molecules have not yet been modified by radiation. The middle eye collects a full 350-wavelength spectrum of surface materials the cameras show to be interesting. These capabilities would allow ELSSIE to rapidly survey the terrain, spot materials of interest for sampling, determine which classes of organic compounds or salts are likely present, and solve for the azimuth, elevation, and distance to the sample. ELSSIE would therefore be extremely enabling for a life-detection mission.

MISSIONS AND FLIGHT INSTRUMENTS

APL is leading or serving as a key partner in several NASA missions scheduled to launch in the next couple of decades that focus on determining habitability and detecting biosignatures. These missions build on prior spacecraft investigations, including the Mars CRISM instrument that observes the Martian surface for compositional information, helping to determine habitable regions in the present and past Martian climate. Additionally, the missions stem from the cutting-edge research and instrument developments that make the habitability and life detection observations and interpretations of data possible.

CRISM Flight Investigation at Mars

As mentioned, the first astrobiology instrument developed at APL was CRISM,[1] which is led by principal investigator Dr. Scott Murchie and was selected for flight on MRO.[2] MRO's objectives tie to habitability in that they include finding sites that may preserve a record of past wet environments, and with these data, researchers can determine which of these environments may have been habitable. MRO's results have shown that aqueous environments were widespread on Mars and, therefore, inform the selection of where to send landed missions to conduct in situ searches for biosignatures and collect samples for eventual return to Earth. CRISM's contribution comes from its images of reflected light from 0.4 to 3.9 μm, in which every pixel has an ~500-wavelength spectrum. CRISM spectra are effective at detecting specific minerals of interest, including silica, clays, and carbonates. These minerals indicate past water with low salinity and moderate pH that could have been habitable, and they would also excel at preserving signatures of any past life that might have taken hold. CRISM's high spatial resolution can detect interesting rock outcrops as small as a tennis court. Its data have been a determining factor—and some members of its team significant players—in selecting sites for the Mars Science Laboratory and Mars 2020 rovers.

Mars Rovers

Dr. Jeff Johnson is a participating scientist on the Mars Science Laboratory Curiosity rover mission, where he works on mission operations and with VISIR reflectance spectra. Those data are provided by the Mastcam multispectral stereo imaging system and through a novel technique in which the ChemCam laser-induced breakdown spectrometer (LIBS) system is used in passive mode (no laser). These data help constrain the composition and mineralogy of rocks and soils encountered along the traverse, which improves understanding of their geologic history.[40–43] Such information also influences decisions regarding which targets to drill and analyze using instruments onboard the rover to help determine the potential habitability of sites encountered within Gale Crater. Anna Martin, a member of APL's technical staff, has recently begun assisting Dr. Johnson with those duties. On the Mars 2020 Perseverance rover (landed February 18, 2021), Dr. Johnson is a co-investigator on two instruments: SuperCam (which expands ChemCam's existing LIBS and VISIR capabilities to include Raman spectra and longer-wavelength infrared reflectance)[44,45] and the Mastcam-Z multispectral stereo zoom camera system.[46] He is preparing to work on mission operations and to use VISIR data from both instruments to help in the selection of samples relevant to habitability that will be cored and cached for eventual return to Earth through the Mars Sample Return Program. APL's Dr. Jorge Núñez is a Mastcam-Z team member and will contribute multispectral data analyses, participate in rover operations, assist with documenting the geologic context of the sampling sites, and help identify samples with high astrobiological potential for caching and eventual return to Earth.

Europa Clipper

Europa, a moon orbiting Jupiter, has an icy exterior but harbors a deep salty ocean beneath. From its slightly eccentric orbit, this world undergoes tidal forcing that not only provides heat that enables its ocean to remain liquid but also may cause hydrothermal activity at its seafloor. This influx of chemistry, along with a potential influx of surface composition from ocean–ice exchange, may allow the reductant-oxidant mixing needed for a habitable environment in Europa's ocean. The Europa Clipper (https://europa.nasa.gov/; Figure 6) mission will explore how habitable Europa's ocean is and seek to understand further its geology, ice shell, ocean, composition, and potential current activity.[47] Several scientists at APL support project science mission development, including one of the deputy project scientists, Dr. Haje Korth. APL is also developing the cameras that will be onboard the Europa Clipper as well as the plasma instrument that is critical in determining ocean existence, thickness, and salinity, and parts of the infrared imaging

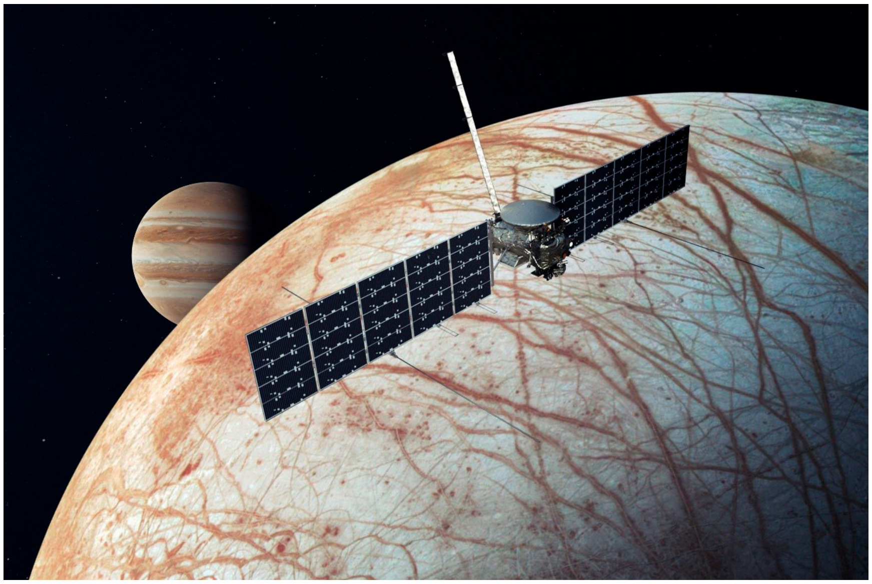

Figure 6. Artist's concept of the Europa Clipper spacecraft in flight above Europa. The mission will explore the habitability of Europa's ocean and improve understanding of its geology, ice shell, ocean, composition, and potential current activity. (Image credit: NASA/JPL.)

spectrometer that will interrogate Europa's composition. These instruments will all contribute tremendously to the mission's overarching goal to explore habitability.

Europa Imaging System Cameras

The Europa Imaging System (EIS) being developed at APL, led by principal investigator Dr. Elizabeth "Zibi" Turtle, is a camera suite made up of a gimbaled narrow-angle camera and a wide-angle camera.[48] Together, these cameras will transform our understanding of Europa's geology, composition, interior, and habitability through a number of carefully crafted imaging campaigns. A plume search will be conducted from as far away as 1,000,000 km to investigate whether Europa's subsurface ocean is actively venting into space. Active plumes could provide a means of sampling a potentially habitable environment that otherwise would be difficult to probe. Repeat color imaging will allow comparisons within the Europa Clipper mission and to Voyager and Galileo data to search for changes and areas coated by fine-grained particulates, both of which could indicate fresh material that was recently exposed at the surface. Global image coverage at <100 m/pixel and regional color and topographic mapping at <25 m/pixel will explore Europa's enigmatic geology, including characterization of possible cryovolcanic structures and correlation of surface features to subsurface structure, to investigate surface to ice shell to ocean exchange processes. Unprecedented local imaging at better than 1 m/pixel will provide the first ever opportunity for an up-close characterization of Europa's surface as well as information at a scale that would inform landing site selection for a future landed mission at Europa.

Plasma Instrument for Magnetic Sounding

The Plasma Instrument for Magnetic Sounding (PIMS) being developed at APL, led by principal investigator Dr. Joseph Westlake, is a Faraday cup–based plasma spectrometer.[49] PIMS has two sensors on the spacecraft, each with two Faraday cups (Figure 7), which are simple sensors that measure the current produced when charged particles impact a metal plate. These plasma measurements are a part of the magnetic induction experiment onboard Europa Clipper that will utilize the rapidly rotating magnetic field of Jupiter to probe the interior of Europa. Simply measuring the induced magnetic field at Europa using the Europa Clipper Magnetometer (ECM) will yield information about the existence of an ocean under Europa's ice shell. The fast-flowing plasma (~200,000 mph) is constantly washing over Europa, creating additional magnetic fields from the charged particle current systems. With the measurements from PIMS, its team will be able to fully constrain the ocean depth, ice shell thickness, and the ocean salinity. PIMS will also be the first instrument to directly sample the charged portion of Europa's ionosphere and could also contribute to the understanding of Europa's plume activity by searching for enhanced magnetospheric activity produced by plume activity.

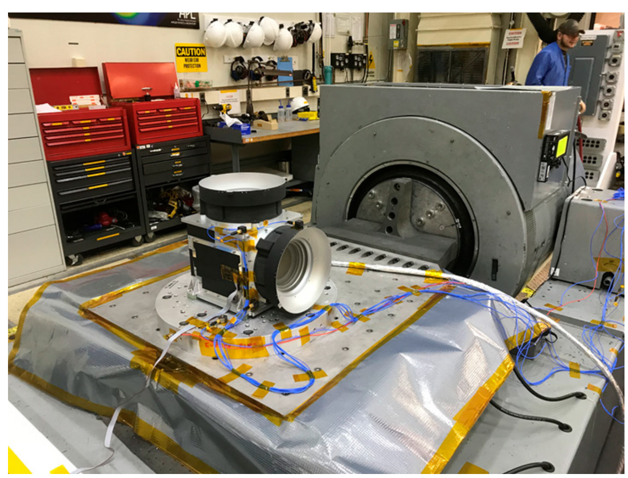

Figure 7. Europa Clipper PIMS engineering model set up for microphonics and vibration testing. PIMS, being developed at APL, is a Faraday cup–based plasma spectrometer. Its measurements will help fully constrain Europa's ocean depth and salinity, as well as its ice shell thickness.

MISE Infrared Spectrometer

The Mapping Imaging Spectrometer for Europa (MISE) is an instrument on Europa Clipper (principal investigator, Dr. Diana Blaney, Jet Propulsion Laboratory [JPL]; deputy principal investigator, Dr. Charles "Karl" Hibbitts, APL) being developed by JPL and APL, with APL's major contributions including provision of the data processing unit, flight software, and the scan mechanism to track Europa's surface. The MISE instrument is designed to radically enhance our understanding of the composition of Europa's ice surface and subsurface ocean.[50] It is a "pushbroom" spectrometer that records infrared spectral images of the surface of Europa to determine surface composition, understand externally versus internally driven processes, and infer subsurface ocean composition. MISE will identify any organics on the surface of Europa and, through mapping their distribution with respect to geologic features, will be able to infer origins as primordial to the moon, exogenous, or originating from the ocean. Active, recent, and past plume activity will be sought and mapped by imaging the spatial distribution and crystallinity of their surficial deposits. Ocean composition will be inferred by identifying the salts and any organics contained both in the European crust and in any plume deposits. Global mapping of composition and texture at a scale of several kilometers per pixel will enable discrimination of global geologic and exogenous processes. Coverage of regional areas at better than 1 km/pixel will enable relating surface composition to individual landforms, and compositional images at as small as tens of meters per pixel will enable MISE to measure the composition of individual geologic units.

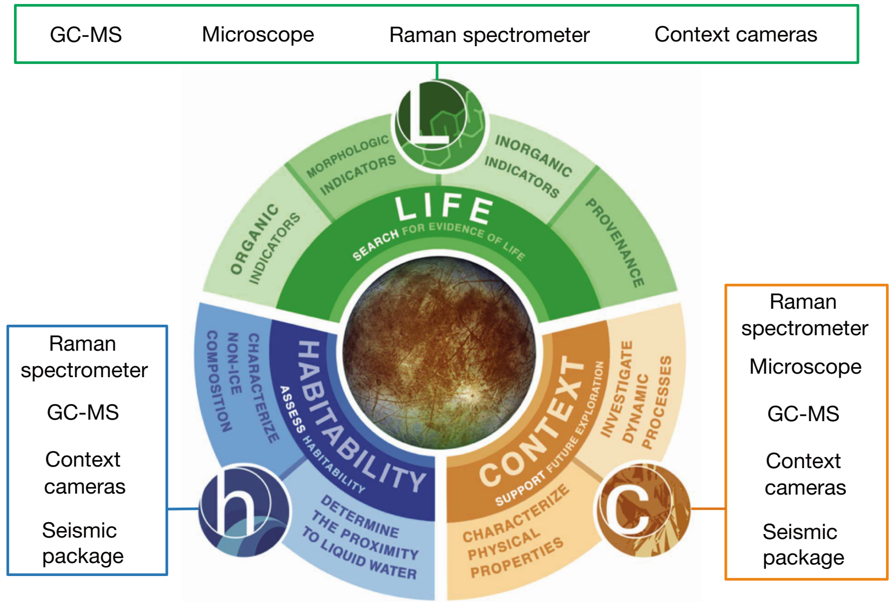

Figure 8. Europa Lander concept science goals and strawman instrument payload. The science of the Europa Lander mission concept focuses on searching for biosignatures in Europa's near subsurface through collecting and analyzing several ice samples from >10 cm depth and assessing habitability and contextual information with in situ techniques. GC-MS, Gas chromatograph–mass spectrometer. (Based on a NASA image from Hand et al.[28])

Europa Lander Mission Concept

The science of the Europa Lander mission (Figure 8) focuses on searching for biosignatures in Europa's near subsurface, through collection and analyses of several ice samples from >10 cm depth. The other goals are to assess the habitability of Europa via in situ techniques uniquely available to a landed mission and to characterize the surface and subsurface properties at the scale of the lander to support future exploration of Europa, as stated in the 2016 Europa Science Definition Team report.[28] The Europa Lander mission concept successfully passed its delta-Mission Concept Review in November 2018, and the team continues to develop sampling tools and techniques as well as autonomy for landing and sampling, and also supports instrument development teams. At APL, Dr. Kate Craft supports the mission's science as a project staff scientist.

Dragonfly

Titan, Saturn's largest moon, is the only moon in the solar system with an appreciable atmosphere. In that nitrogen-methane atmosphere, energetic particles from the Sun, Saturn's magnetic field, and even galactic cosmic rays initiate photolytic chemistry to create a variety of organic molecules, called aerosols. These molecules range from simple hydrocarbons and nitriles to complex unknown species of the same size as proteins here on Earth. This level of chemical complexity is unparalleled elsewhere in the solar system, except on Earth where biochemistry facilitates reactions that would otherwise be energetically prohibitive. Furthermore, the products of this atmospheric chemistry fall across Titan's surface and may be physically and chemically reworked by the myriad of geological processes acting on the surface. Titan is therefore *the* solar system destination for understanding how far prebiotic chemistry can progress, providing a crucial link in our understanding of whether life may (or may not) arise elsewhere in the universe.

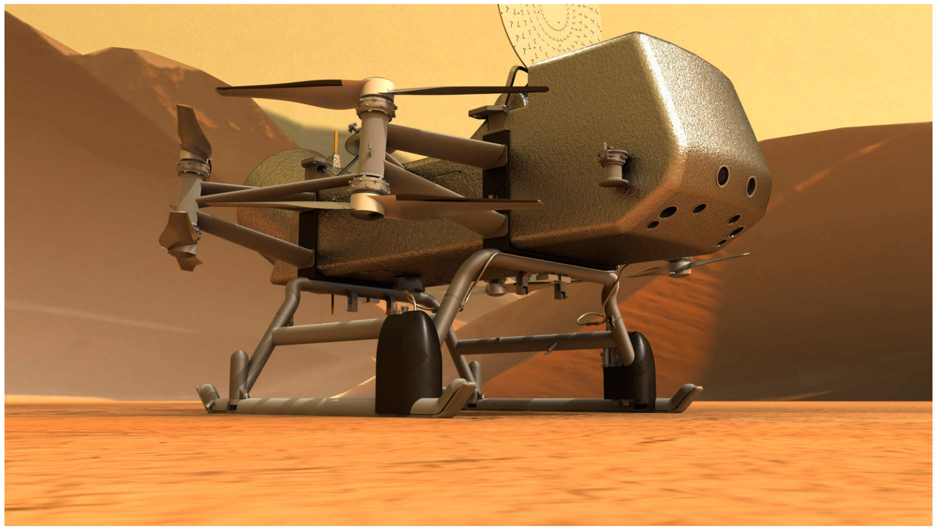

Figure 9. Artist's rendering of the Dragonfly rotorcraft lander. While mobility is key to achieving Dragonfly's science objectives, Dragonfly will spend most of its time doing science on Titan's surface.

The Dragonfly mission[51] will send a rotorcraft lander (https://dragonfly.jhuapl.edu/; Figure 9) to collect the results of the prebiotic experiments of Titan's natural laboratory. Led by APL scientist Dr. Elizabeth "Zibi" Turtle, Dragonfly is the fourth mission selected as part of NASA's New Frontiers program, the largest competitive program for planetary missions. After a 9-year cruise, Dragonfly will make its first landing on Titan in 2036 and begin its science mission: determining the chemical composition of Titan's surface materials; characterizing how these materials are moved and modified by geological and meteorological processes; constraining the likelihood of interaction between the organic-rich surface and subsurface ocean; and searching for evidence of past or extant life. Though Titan's surface is probably too cold for extant Earth-like life, Dragonfly will be capable of detecting biomarkers indicative of extinct life, such as looking for patterns like enantiomeric (left- or right-handedness) excess in its survey of amino acids. These kinds of measurements are agnostic to the biology responsible, and thus might enable detection of "alien" life that uses the liquid hydrocarbons available on Titan's surface as the solvent for biochemistry.

Cryobot Exploration of Ocean Worlds

As we look a bit more into the future, we plan to not only land on these intriguing ocean worlds but also transverse through the ice to their oceans below.[52,53] We can only imagine what amazing discoveries await at Europa and Enceladus in particular, because of their high potential for habitable oceans with energy and the ingredients to support life. Studies have been performed to understand the challenges inherent to such a subsurface access mission, including power, navigation, thermal control, communication, planetary tectonic, radiation, and composition hazards, and the scientific instrument payload that would be able to interrogate the ice shell for signs of life and geophysical data as the cryobot travels to the ocean (Figure 10). Dr. Kate Craft participated in two studies on the feasibility and detailed design of cryobots to access the ocean of Europa.[54,55] The first, performed with the NASA Glenn Research Center, designed a mission architecture to traverse through 20 km of ice to reach the ocean in less than 3 years with nuclear power

Figure 10. Artist's concept of a cryobot traversing the ice shell and reaching the ocean. (NASA image from Oleson et al.[54]).

sources. The second mission study, performed with NASA's JPL, focused on a radioisotope-powered, pressure vessel type. Dr. Craft is also currently leading a NASA SESAME (Scientific Exploration Subsurface Access Mechanism for Europa) grant with APL co-investigators Dr. G. Wes Patterson and Dr. Ralph Lorenz and co-investigators at the Woods Hole Oceanographic Institute, SwRI, and Lamont-Doherty Earth Observatory to evaluate the performance of tethered and free-space communication techniques for cryobots such as these, to ensure that the critical science discoveries can be communicated robustly back to the surface for transmission to Earth. These missions are the next steps for exploring ocean worlds. Rather than rove on the surface, robots will probe the depths.

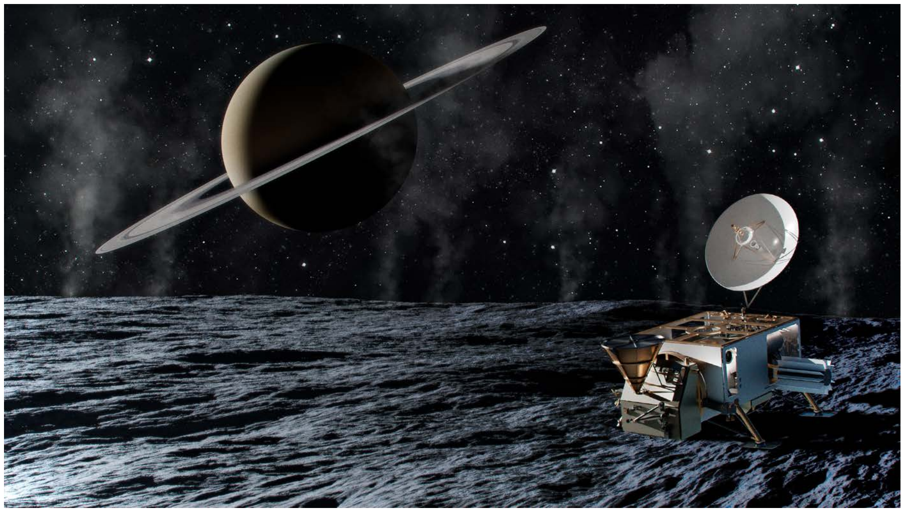

Figure 11. Enceladus Orbilander spacecraft concept. In this concept, for which a study report was submitted to the National Academies to inform the mission and science priorities in 2023–2032, the spacecraft would collect samples both from orbit and on the surface, robustly addressing not only whether biosignatures are present but also why or why not.

PLANETARY SCIENCE AND ASTROBIOLOGY DECADAL STUDIES FOR 2023–2032

NASA funded 11 community studies of potential new mission concepts to inform the mission and science priorities in 2023–2032 set by the Planetary Science and Astrobiology Decadal Survey conducted by the National Academies. Of these, two astrobiologically relevant mission studies were led by APL principal investigators.

Enceladus Flagship

At the heart of astrobiology is the search for life elsewhere in the universe. Saturn's moon Enceladus offers a unique opportunity to conduct such a search with technology available today and in the near future. The Cassini mission discovered that the plumes of ice particles and water vapor that emanate from Enceladus's south pole are ultimately sourced from a warm, salty subsurface ocean. Thus, Enceladus's ocean is available to sample either in space (flying through the plume) or on the surface (catching falling plume material or scooping freshly fallen deposits). Working with the APL concurrent engineering team under the direction of systems engineers Karen Kirby and Peter Greenauer, a team of scientists led by APL researcher Dr. Shannon MacKenzie evaluated which architecture maximized science return per dollar. The resulting concept, Orbilander[56] (Figure 11), would collect samples both from orbit and on the surface, robustly addressing not only whether biosignatures are present but also why or why not. The study report has been submitted to the National Academies.

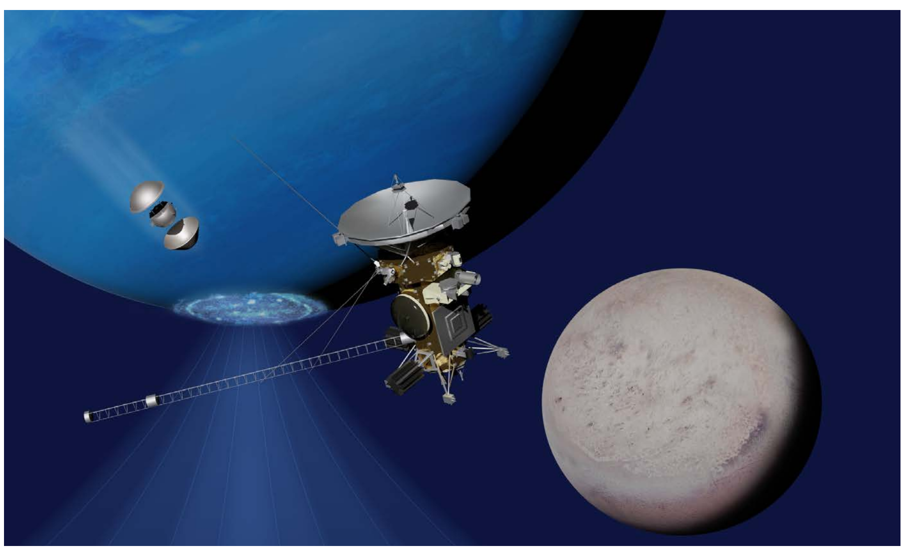

Figure 12. The Neptune-Odyssey spacecraft and atmospheric probe concept to explore the Neptune-Triton system. Neptune-Odyssey would investigate whether Triton is an ocean world, what causes its plumes, and ascertain its astrobiological potential.

Neptune Flagship

A Flagship-class mission concept study team led by Dr. Abigail Rymer and colleagues delivered its report to the National Academies in August 2020. The mission, if prioritized to go forward, will launch a Cassini-like spacecraft and Neptune atmospheric probe to the Neptune-Triton system in the early 2030s, arriving in the late 2040s[57] (Figure 12). Triton was observed by the Voyager 2 spacecraft to be home to active outgassing, with plumes and evidence of ancient outgassing seen across the southern hemisphere. At the time the observations were assumed to be associated with solar-driven sublimation from the frigid mostly nitrogen ice surface—interesting, but of little realistic astrobiological potential. Subsequent to the Voyager Grand Tour of the 1970s and 1980s, the Cassini mission to the Saturn system in the 2000s discovered active jets at Enceladus, and the New Horizons flyby of Pluto revealed dynamic atmospheric conditions and resurfacing, both of which indicate that signs of liquid water exist in places we had hitherto assumed were lacking sufficient energy to be of viable astrobiological interest. A return to the Neptune-Triton system with an orbiting spacecraft will enable the comprehensive study of Neptune's captured moon, Triton, itself slightly larger than Pluto and also originally a dwarf planet in the Kuiper Belt. The mission, named Neptune-Odyssey, would spend 4 years mapping Triton and the Neptune system, providing humanity's most thorough investigations into the astrobiological potential of this distant, active world.

LOOKING FORWARD

Through these projects and those that will follow, APL is striving to make major contributions to the field of astrobiology. APL seeks to be a go-to lab for expertise and experience in sample preparation, sample handling, and biosignature-detection instrumentation for spaceflight, as well as a known leader in astrobiology research and missions. In the next 25 years, it is possible that APL's Dragonfly mission will have discovered amino acids indicating a potential biologic origin and that the Europa Clipper mission will have characterized Europa's ocean as a habitable environment rich in the ingredients needed for life. APL would then also be part of follow-on missions to land on Europa's and Enceladus's surfaces and interrogate for biosignatures and potentially discover signs of extant life. With APL investigators, Mars rovers may detect signs of past habitability and returned samples may contain preserved evidence of early Martian life, while additional missions may probe the ice giants and their moons, possibly discovering more ocean worlds. Next-generation APL-built instruments, including one capable of purifying and characterizing organisms present in distant worlds, could be part of a NASA life-detection mission to Mars or an ocean world, making discoveries alongside other APL instruments that could characterize biosignatures and observe environmental and geophysical context. The future of astrobiology at APL is bright!

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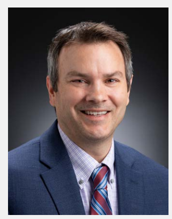

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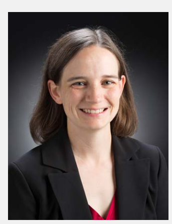

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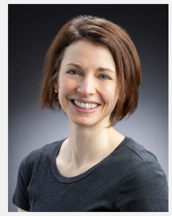

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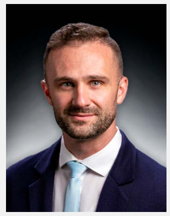

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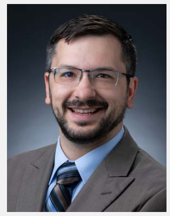

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