National Aeronautics and Space Administration

NASA Astrobiology Institute 2016 Annual Science Report

Team Report:

Virtual Planetary Laboratory,
University of Washington, Seattle

The Virtual Planetary Laboratory

Lead Institution:
University of Washington, Seattle

Principal Investigator:
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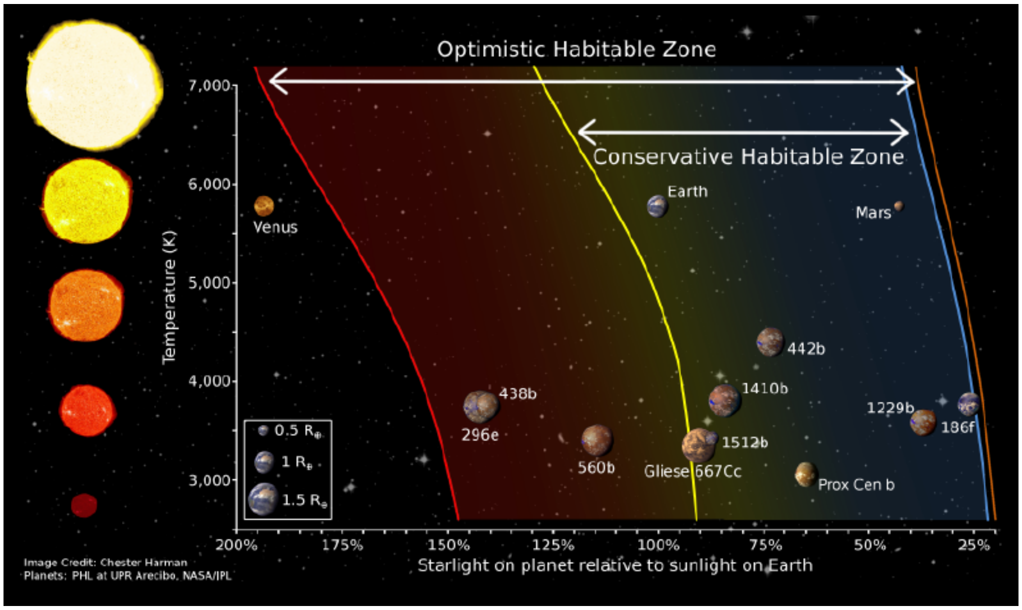
Team Overview

Identifying a habitable or inhabited planet around another star is one of NASA's greatest long-term goals. Major advances in exoplanet detection place humanity on the brink of finally answering astrobiology's over-arching question: "Are we alone?", but there are still many scientific steps required before we can identify a living world beyond our Solar System. The Virtual Planetary Laboratory focuses on understanding how to recognize whether an extrasolar planet can or does support life. To do this, we use computational models to understand the many factors that affect planetary habitability, and use models, field and laboratory experiments to better understand how life might impact a planetary environment in detectable ways. These results are used to determine the potentially observable planetary characteristics and the telescope measurements required to discriminate between planets with and without life. Our five research objectives are to:

- Characterize habitability and biosignatures for an Earth-like planet
- Characterize the environment, habitability and biosignatures of the Earth through time
- Develop interdisciplinary, multi-parameter characterization of exoplanet habitability
- Determine the impact of life on terrestrial planet environments and the generation of biosignatures
- Define required measurements and optimal retrieval methods for exoplanet characterization missions

Team Website: https://depts.washington.edu/naivpl/content/welcome-virtual-planetary-laboratory

2016 Executive Summary



VPL researchers worked this year to refine the limits of the Habitable Zone, the region around a star where an Earth-like planet could have liquid water on its surface. They also studied Proxima Centauri b, a nearby, potentially terrestrial planet whose position in its star's habitable zone is shown here.

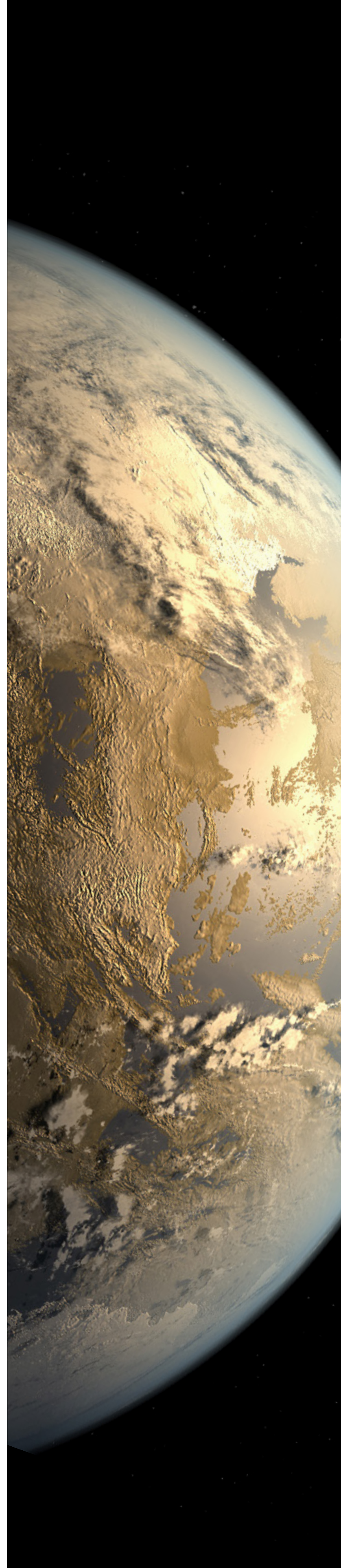
To enable NASA's search for life beyond the Solar System the Virtual Planetary Laboratory Team uses computer models to explore terrestrial exoplanet habitability and biosignatures. The interdisciplinary VPL exoplanet models use Earth and Solar System observations, Earth's geological history, and laboratory and field work, to enhance the science return from NASA exoplanet missions.

In Task A, we use Earth and other Solar System data to explore planetary processes and habitability detection, and to validate exoplanet models. This year we used sophisticated models of Earth to test retrievals of planetary parameters by future telescopes. We observed water plumes as Europa transited Jupiter (Sparks et al., 2016), and used general circulation models (GCM) to show that Venus may have been habitable up until 0.7 Gy ago (Way et al., 2016).

In Task B we explore the atmosphere, interior and biosphere of the alternative habitable environments provided by the Earth though time. Our research coalesced around understanding nitrogen— as an atmospheric gas controlled by both biological and abiotic processes (Wordsworth et al., 2016a), and as a potential early isotopic biosignature (Stüeken et al., 2016). Our measurements suggest that Earth's atmospheric N_2 2.7 Gya was less than half the modern amount (Som et al., 2016). We modeled a hydrocarbon haze in the Archean (< 2.5 Gy ago), which could have cooled the planet, shielded the surface from UV radiation, and acted as a biosignature (Arney et al., 2016).

In Task C, we study star-planet interactions and their impact on habitability. We performed a rapid-response, massively interdisciplinary modeling study of plausible evolutionary scenarios for the habitable zone planet Proxima Centauri b (Barnes et al., 2016). We modeled densely-packed M dwarf planetary systems (Bolmont et al., 2016) and habitable zone limits for synchronously-rotating planets (Kopparapu et al., 2016).

In Task D, we use modeling, laboratory and field work to understand the co-evolution of the environment and biosphere, and to help identify new biosignatures and false positives. We studied life's early evolution (Black & Blosser, 2016; Dacks et al., 2016),



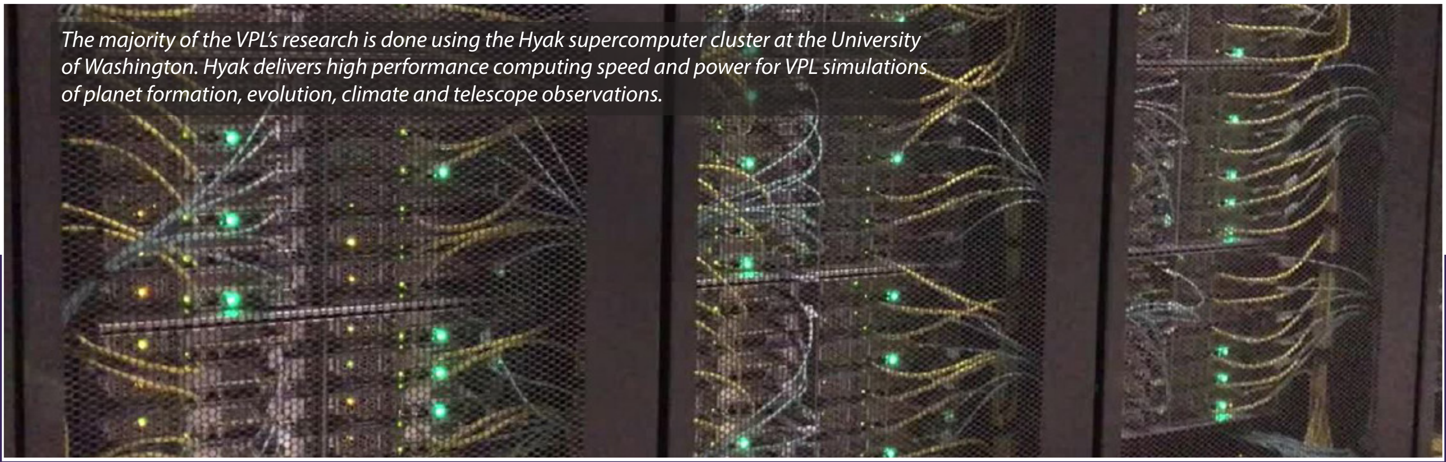
The Pongola Supergroup in Western Australia comprises rocks that formed around 3.0-2.9 billion years ago in the Archean eon, long before the rise of oxygen in Earth's atmosphere. VPL researchers study biosignatures and environmental parameters recorded by these rocks to determine the constraints and capabilities of a largely anaerobic biosphere, which represents a habitable planetary environment unlike modern Earth.

Astrobiology graduate student Michael Kipp gathering soil samples in the Muir Snowfields in Mount Rainier, Washington during an astrobiology training workshop. Snowfields like Muir are home to extremophile organisms that could arise and thrive in extreme conditions on other planets.

and identified the combination of N_2, O_2 and an ocean as Earth's strongest disequilibrium biosignature (Krissansen-Totton et al., 2016a).

In Task E, we use environments generated in Tasks A-D to quantify the detectability of planetary characteristics, including habitability and biosignatures, for current and future telescopes. We modeled plausible current environments and spectra for Proxima Cen b (Meadows et al., 2016), and identified observational discriminants for abiological sources of O_2 (Schwieterman et al., 2016). We improved planet detection algorithms (Agol & Deck, 2016; Deck & Agol, 2016; Luger et al., 2016), and explored photometric characterization of exoplanet environments (Krissansen-Totton et al., 2016b).

VPL Team members contributed to science or design for several NASA missions, including detection algorithms for Kepler/K2 (Luger et al., 2016); target selection and simulated terrestrial exoplanet observations for JWST; participation in the WFIRST mission, and HabEx/LUVOIR mission concepts; and membership on the ExoPAG Executive Council. In EPO, we implemented two astrobiology-themed Science on a Sphere shows, and developed a hands-on temporary museum exhibit on Biosignatures.

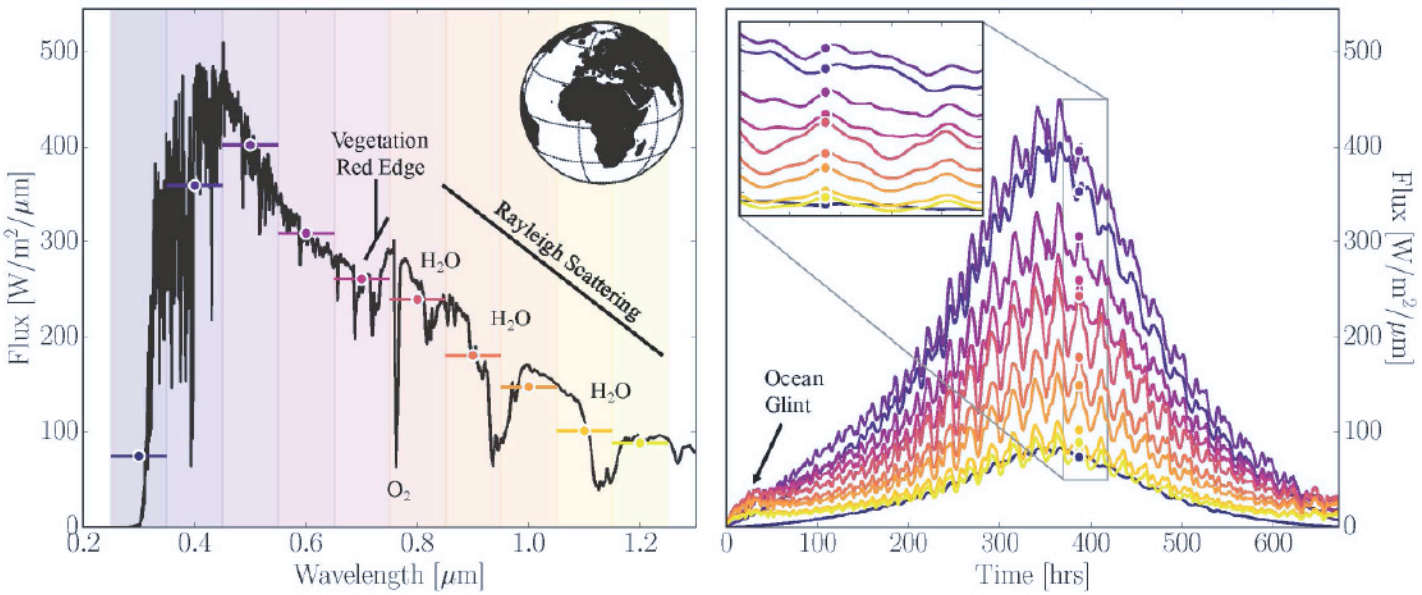


The majority of the VPL's research is done using the Hyak supercomputer cluster at the University of Washington. Hyak delivers high performance computing speed and power for VPL simulations of planet formation, evolution, climate and telescope observations.

Project Reports

Task A: Solar System Analogs for Extrasolar Planetary Processes and Observations

In this task, observations of Solar System planets and moons are used to explore planetary processes, determine remote-sensing discriminants for habitable environments, and validate exoplanet models. This year we addressed these goals using observations of Europa, models and observations of Venus, and the properties of Earth and Mars. Sparks et al. (2016) took HST/STIS observations that provided exciting evidence for plumes on Europa. They observed Europa as it transited across Jupiter, and the backlighting from Jupiter revealed patches of UV absorption from water off the limb of Europa. This remote-sensing opportunity allows study of the ocean below the ice, which is one of the most plausible sites for extant life beyond Earth. Gao et al. (2016) used microphysics models to constrain ice particle size and total mass in the plumes of Enceladus. GCM model simulation of early Venus in NExSS-initiated work was used to understand Venus as an analog for terrestrial planets that are close to their stars (Way et al., 2016). This work showed that the rotation period of the planet was crucial in understanding its planetary climate, and that even with its current rotation period, Venus could have been habitable as recently as ~0.7 Gya. Schwieterman and colleagues simulated the Earth as seen from the Moon to create a phase-dependent dataset for studying the Earth as an exoplanet. Lustig-Yaeger and colleagues used this dataset to develop new photometric mapping techniques for terrestrial exoplanets. Robinson and colleagues used observations of Venus, Earth and Mars to validate the VPL's new 1-D radiative-convective-equilibrium model, providing a powerful new tool for modeling of a diversity of exoplanet environments, including terrestrial planets orbiting M dwarfs.



The VPL 3D spectral model simulates Earth as an exoplanet, and includes oceans, land, ice, vegetation, atmosphere, and clouds. (Left) The disk-averaged spectrum of the Earth seen in reflected light (flux) for the view of Earth seen in the upper right of this panel. The sharp rise in reflected light near 0.7μm is due to the vegetation red-edge. (Right) The Earth's disk-integrated reflected light brightness as a function of time for the Earth as seen from the Moon, at different wavelengths. Lower values of brightness are for crescent phase as seen from the Moon, and brightness increases towards full phase. Variations in these curves can reveal the distribution of continents and oceans, and their colors. This VPL simulated dataset of Earth is then passed through a coronagraph instrument simulator, and this data is used to retrieve the telescope and instrument parameters needed to measure planetary rotation rate and provide surface maps.

Task B: Early to Current Earth and Mars

We study early Earth and Mars to better understand potentially habitable planetary environments that are very different to our modern Earth. This year we further constrained the properties of the atmosphere, interior and biosphere of the early Earth, and explored factors affecting the climate of early Mars. Studies of Earth's ancient nitrogen showed that biogeochemical nitrogen cycling rates varied over the Earth's history (Stüeken et al., 2016a), that nitrogen in 3.7 billion year old metasediments could only have been produced by biological nitrogen fixation, and so is a potential biosignature (Stüeken et al., 2016b), and that abiotic nitrogen sources would have been inadequate to support a large early biosphere, favoring the early evolution of biological nitrogen fixation (Stüeken et al., 2016c). Wordsworth (2016) reviewed biotic and abiotic mechanisms governing nitrogen exchange between a terrestrial planet's surface and interior, showing that oxidation of a planet's mantle via photolytic atmospheric water loss could enhance N_2 release into the atmosphere. Som et al. (2016) analyzed the volume of bubbles trapped in 2.7 billion year old lava flows and concluded that the atmosphere then was significantly less massive than today's. Arney et al. (2016) modeled the environmental impact of a hydrocarbon haze in the Archean Earth's atmosphere, finding that habitable conditions could be maintained, and that surface UV flux would be significantly reduced. The haze also produced strong spectral features. Team members reviewed climate results for early Mars (Wordsworth, 2016b), demonstrated a connection between the timing and morphology of Martian stratigraphic deposits and evolution of the planet's obliquity (Kite et al., 2015), and postulated a geophysical mechanism for extended periods of glaciation on Mars punctuated by warm epochs lasting for up to 10 million years (Batalha et al., 2016). Team members also contributed to a hypothesis for near-surface methane exchange (Hu et al., 2016).

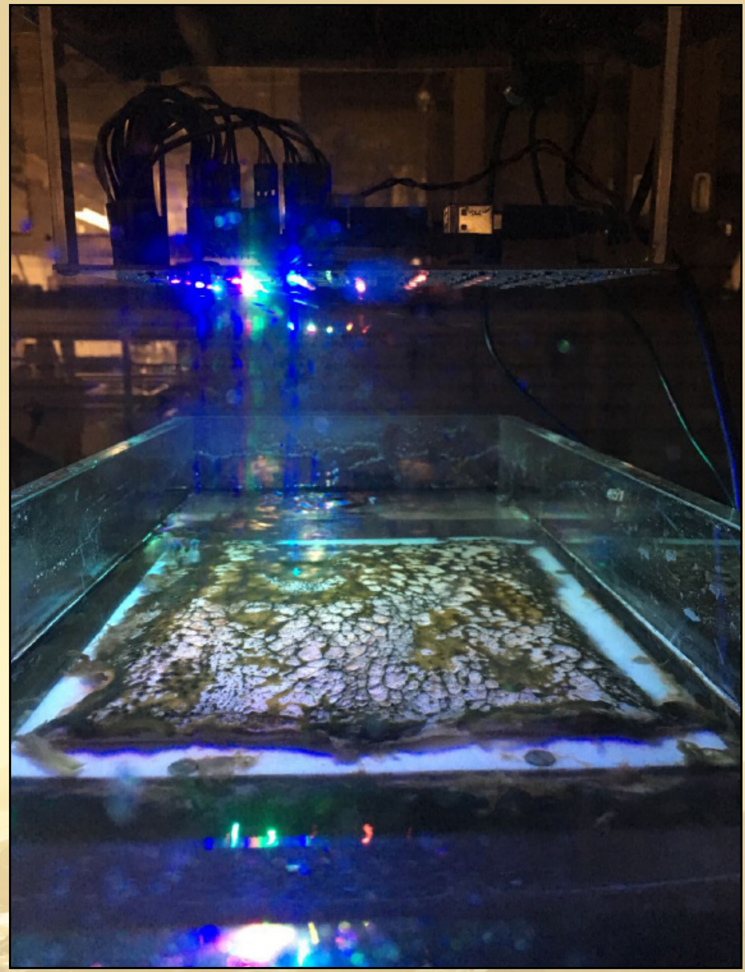
Task C: The Habitable Planet

Here we study the interactions between a planet, its star, and other planets in the system, which can strongly affect habitability. Research this year included modeling of planet formation, and internal, orbital and atmospheric evolution for M dwarf terrestrial planets. Many VPL Team members participated in a rapid-response, massively interdisciplinary effort to study the evolution and potential habitability of the newly discovered planet Proxima Centauri b (Barnes et al., 2016), an M dwarf habitable zone (HZ) terrestrial. We found a diversity of plausible scenarios under which this HZ planet could support or have lost surface liquid water. Team members also contributed to another study on the evolution of the irradiation, rotation, and volatile inventory for Proxima Cen b (Ribas et al., 2016). Shields et al. (2016a) reviewed the occurrence rate and habitability of M dwarf planets. Raymond looked at the effects of planet-planet interactions in densely packed M dwarf planetary systems (Bolmont et al., 2015). Backus and Quinn (2016) modeled the evolution of protoplanetary disks around M dwarf stars and found that giant planets may form rapidly, affecting terrestrial planet formation. To better understand the habitable zone's inner edge, Ding and Pierrehumbert (2016) developed a climate convection scheme for atmospheres with high condensable gas fractions, and Abbot explored fundamental atmospheric processes for tidally locked Earth-like planets (Koll & Abbot, 2016). Kopparapu et al. (2016) showed that the rapid rotation of tidally-locked M dwarf planets may smear cloud patterns and drop planetary albedo, pushing back the habitable zone inner edge. At the outer edge, Haqq-Misra et al. (2016) followed Abbot (2016) and explored the limit cycle concept for planets with low volcanic outgassing rates, narrowing the habitable zone for planets around Sun-like stars. Shields et al., (2016b) identified plausible combinations of orbital and atmospheric properties that allow habitability for Kepler-62f.

Artist's impression of the planet recently discovered orbiting Proxima Centauri, the Sun's closest neighboring star. This planet, Proxima Centauri b, sits in this star's conservative habitable zone, and is an exciting target for follow-up observations by future space- and ground-based observatories to search for signs of habitability and life. VPL researchers characterized Proxima b's potential evolutionary history, habitability, and determined the requirements for future observations.

Task D: The Living Planet

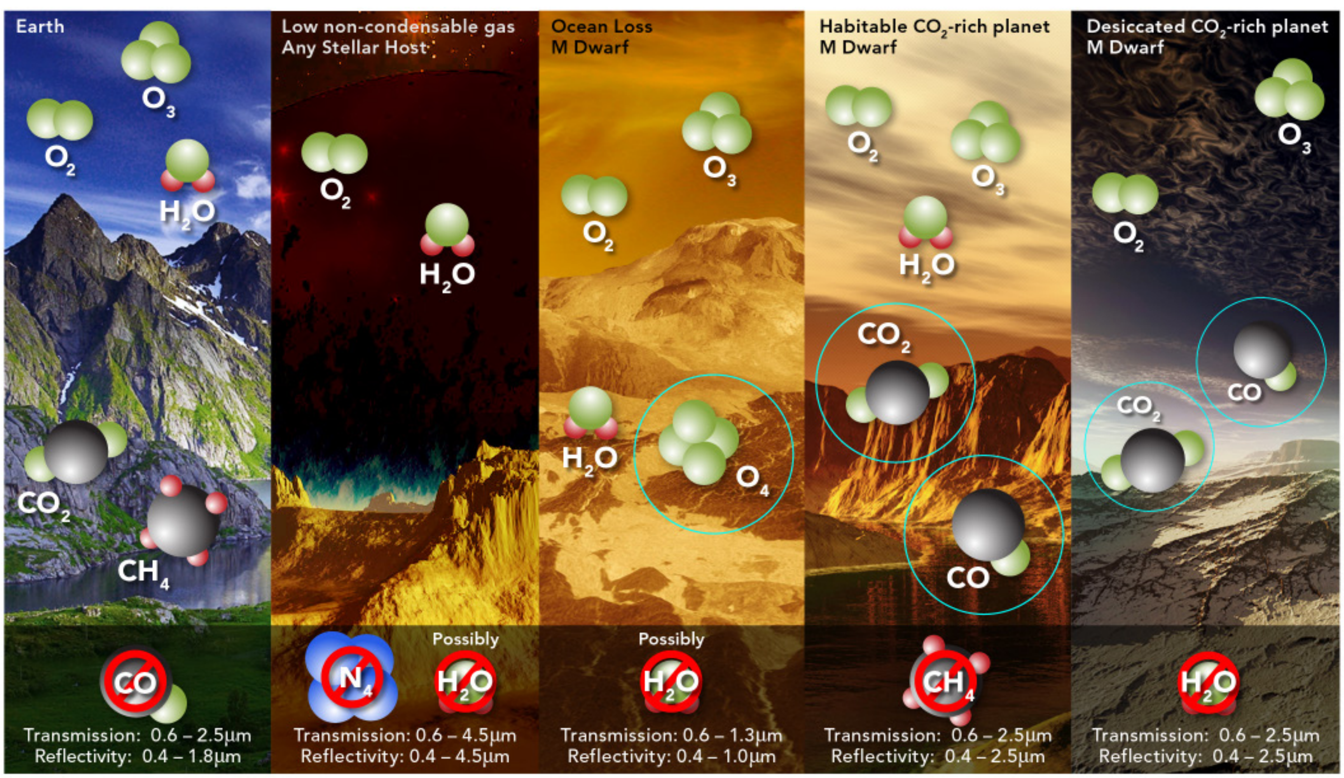
Modeling, laboratory, and field work are used to understand the co-evolution of the environment and biosphere, identify new remotely-detectable biosignatures, and understand the potential for planetary environments to generate false positives for life. This past year we studied life's early evolution, surface photosynthetic biosignatures, and quantified disequilibrium biosignatures in planetary environments. Black proposed that self-assembled aggregates of fatty acid membranes and the building blocks of biological polymers provides a first step in the emergence of protocells (Black & Blosser, 2016). Buick and colleagues reviewed the origins of eukaryotic organisms and argued that complex cells arose from simple prokaryotic precursors within the Archaea (Dacks et al., 2016), and may be less specialized than previously thought. Baross contributed to studies of the nature and limits of life in hydrothermal vent chimney environments, as analogs for understanding the potential for subsurface life on planets and moons (Lin et al., 2016). Siefert wrote a book chapter on life in desiccated environments. Parenteau and collaborators measured the reflectance spectra of environmental samples of anoxygenic phototrophs, detecting photosynthetic pigments from all layers of the microbial mat in a "community biosignature" that may be remotely detectable. They also started experiments on microbes in laboratory Archean atmosphere environments. Krissansen-Totton et al. (2016) showed that the Earth's biosphere helps to give it 20 times the thermodynamic chemical disequilibrium of other planets. They identified the simultaneous presence of N_2, O_2 and an ocean as the strongest disequilibrium biosignature for our planet. Ongoing work looks at circular polarization signals from anoxygenic phototrophs, as well as field sampling and lab isolations to study far-red light harvesting antennas for oxygenic photosynthesis. These pigments may be relevant to organisms adapted to the early, haze-covered Earth, or on planets orbiting M dwarfs, where photosynthetically-active radiation may be dominated by longer wavelengths.



Microbial mats are grown in the laboratory in a simulated Archean atmosphere illuminated by the spectrum of different types of stars. These VPL experiments help us understand how early life may have modified its planetary environment, and the effect a star's light has on microbial mat structure and metabolism. Modifications to the planetary environment that can be attributed to biology could provide evidence for life on other planets. Credit: Niki Parenteau (NASA Ames)

Task E: The Observer

In Task E the environments generated in Tasks A-D are used to improve terrestrial exoplanet detection and target selection, and to quantify the detectability of exoplanet habitability and biosignatures using current and future telescopes. This year, our highlights included modeling plausible environments for Proxima Centauri b, and developing a comprehensive framework for identifying false positives for the O_2 biosignature. We also improved terrestrial planet detection algorithms, and worked on exoplanet observational characterization techniques and models, including spectral retrieval. Meadows et al. (2016) simulated the current environmental states and observational discriminants for Proxima Cen b, building on the plausible evolutionary scenarios described in Barnes et al. (2016; Task C). Although Proxima Cen b sits squarely in the habitable zone, we showed that evolutionary processes may have rendered it uninhabitable, although habitable scenarios were also possible. Synthetic spectra for Proxima Cen b identified O_2 and O_4 due to ocean loss, and CO from CO_2 photolysis as potential observational discriminants for false positive O_2 (previously identified in Schwieterman et al., 2016). Raymond participated in another study of Proxima Cen b's habitability (Turbet et al., 2016). Luger et al., (2016) explored the feasibility of detecting auroral oxygen on Proxima Cen b using high-resolution spectroscopy. Luger et al., (2016) developed the EVEREST pipeline to recover the photometric precision of the Kepler/K2 mission, and detect more Earth-sized planets. We developed transit timing theory (Agol & Deck, 2016; Deck & Agol, 2016), to enable target selection based on planetary densities, and to measure masses for Kepler super-Earths (Jontoff-Hutter et al., 2016). We identified optimal broadband photometric discrimination of exoplanet environments (Krissansen-Totton et al., 2016), and surveyed the capabilities of coronagraphic telescopes for potentially habitable terrestrial planets (Robinson et al., 2016). We also improved radiative transfer models (Kopparla et al., 2016), adding polarization capability (Kopparla et al., 2016).



VPL has pioneered the study of potential "false positives" for the O_2 biosignature in planetary atmospheres. False positives are ways that O_2 can be generated by the planet itself, instead of by life, and depend largely on processes like atmospheric loss and photochemistry. This figure shows several combinations of host star and planetary environment that could produce false positives. It also identifies molecules that might be seen in planetary spectra that will help us recognize if the oxygen is due to life or planetary processes.

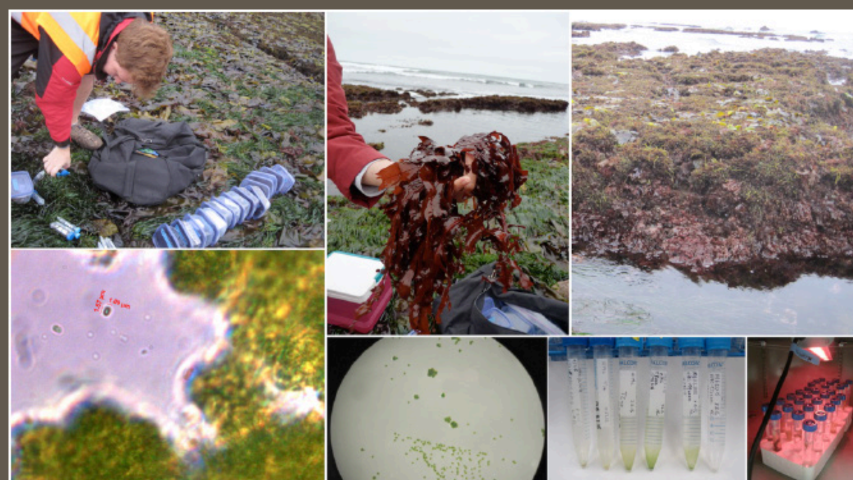
Field Work

The VPL Team conducted field work in four locations, South Africa, Mexico, California, and Washington, to understand life in extreme conditions and to identify the chemical and isotopic signatures of Earth organisms to help guide our search of biosignatures in atmospheres of other planets.

The Pongola Supergroup is a grouping of Mesoarchean rocks in South Africa that can inform us about the early evolution of life on Earth. Biosignatures and environmental parameters recorded by these rocks can inform us about the constraints and capabilities of a largely anaerobic biosphere. The modern Wit-Umfolozi River has cut through the Pongola Supergroup and created a cross section through the major geological units, an ideal locality for gaining an overview of stratigraphic relationships. This summer we had a reconnaissance trip of the Pongola Supergroup as well as other Archean terrains to establish contacts with local geologists and plan for collaborative sample collection activities in the future.

Cuatro Cienegas is an oasis in the desert of northern Mexico that is inhabited by an uncommon diversity and endemicity, prospered by a highly unbalanced stoichiometry. It provides an opportunity to understand the evolution of microbial communities in an *in situ*, closed, controlled environment. This is important because it allows us to evaluate exactly how communities diversify in real time and a real place. We performed *in situ* experiments as well as

The Pongola Supergroup comprises sedimentary and igneous rocks that formed around 3.0-2.9 billion years ago, long before the rise of oxygen in Earth's atmosphere.



Far-red oxygenic photosynthesis field site, Montara State Marine Reserve, Moss Beach, California. Clockwise from upper left: Intern Cameron Hearne collecting red algae on which far-red cyanobacteria are epiphytes; Erythrophyllum delesseroides, one of numerous red algae species at the site; low tide reveals layering of green algae at the surface and red algae deeper in the photic zone; lab enrichment cultures under 703 nm LED light; colonies; cells of Acaryochloris unnamed strain.

Cuatro Cienegas in northern Mexico, inhabited by an uncommon diversity and endemicity.

extensive microbial censuses of a well-defined hydrologic system (the Churince) subject to natural climactic variations. Our results provide a picture of real time evolution in microbial communities in concert with the geology and nutrient availability.

Montara State Marine Reserve is an intertidal reef area on the Central California Coast that supports abundant marine life, including red macroalgae. Previous visits to the site confirmed the presence of a Chlorophyll *d*-containing organism. Chl *d* is currently the only known pigment other than chlorophyll *a* able to serve as the primary photopigment in oxygenic photosynthesis. Its spectral absorbance in the far-red/near-infrared makes it a model for how the primary photosynthetic pigment on exoplanets with redder stars may be adapted to exhibit alternative spectral absorbance features. Samples were collected and measurements were made for later modeling of the spectral light environment of these organisms and purified cultures are being prepared for full genome sequencing to understand the evolutionary path of *Acaryochloris*.

The Muir Snowfield on Mt Rainier, WA, is a high-altitude permanent snowfield interspersed with rock, sand, and piles of pumice and volcanic ash. These snowfields present many extreme conditions, among which are high pressures, strong winds, limited nutrients, limited liquid water, and extremely low temperatures. Studying life in these fields help astrobiologists better understand life in extreme conditions. Soil and snow samples were taken from the Muir Snowfields to test for ATP as an *in situ* life-detection sampling technique.

Virtual Planetary Laboratory: 2016 Publications

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