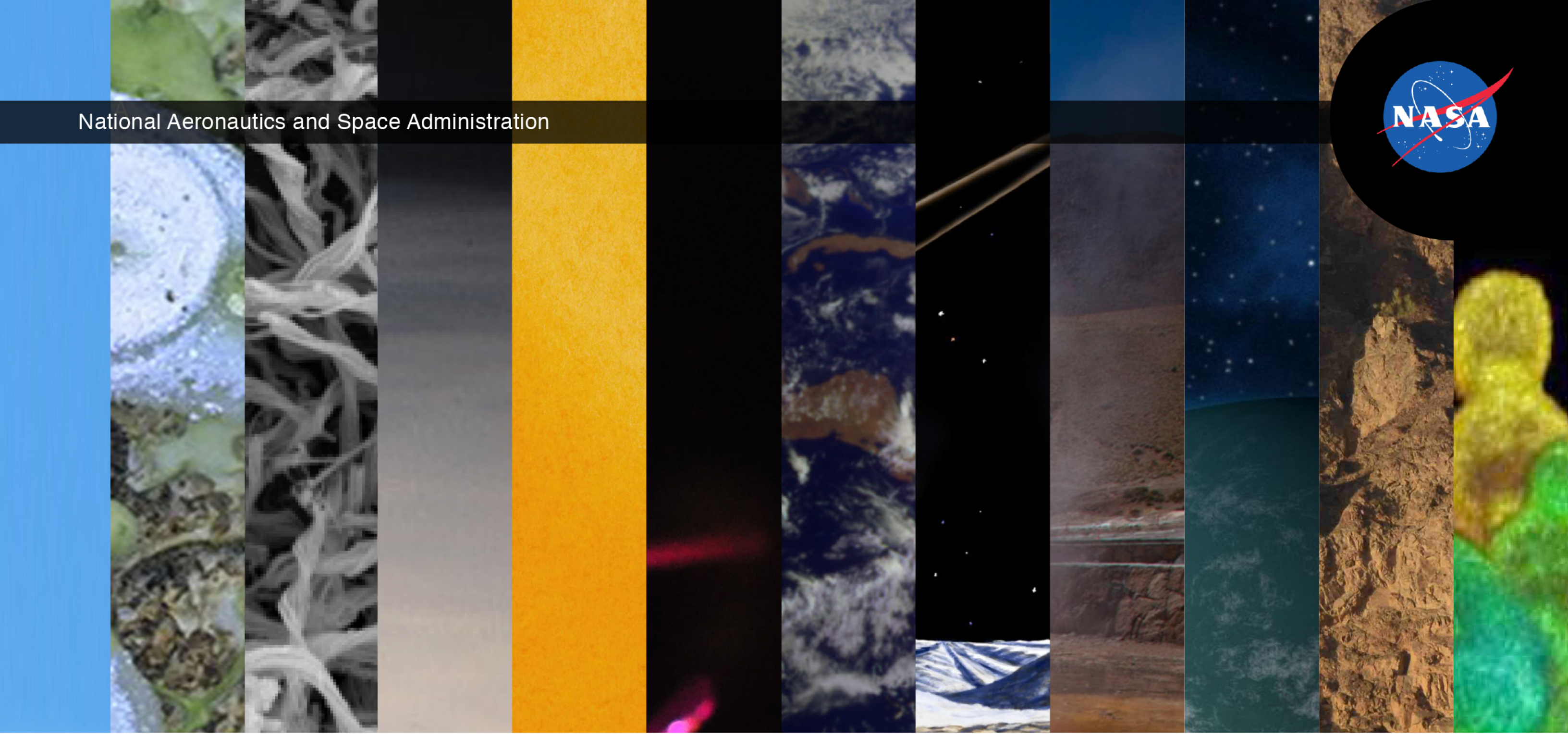
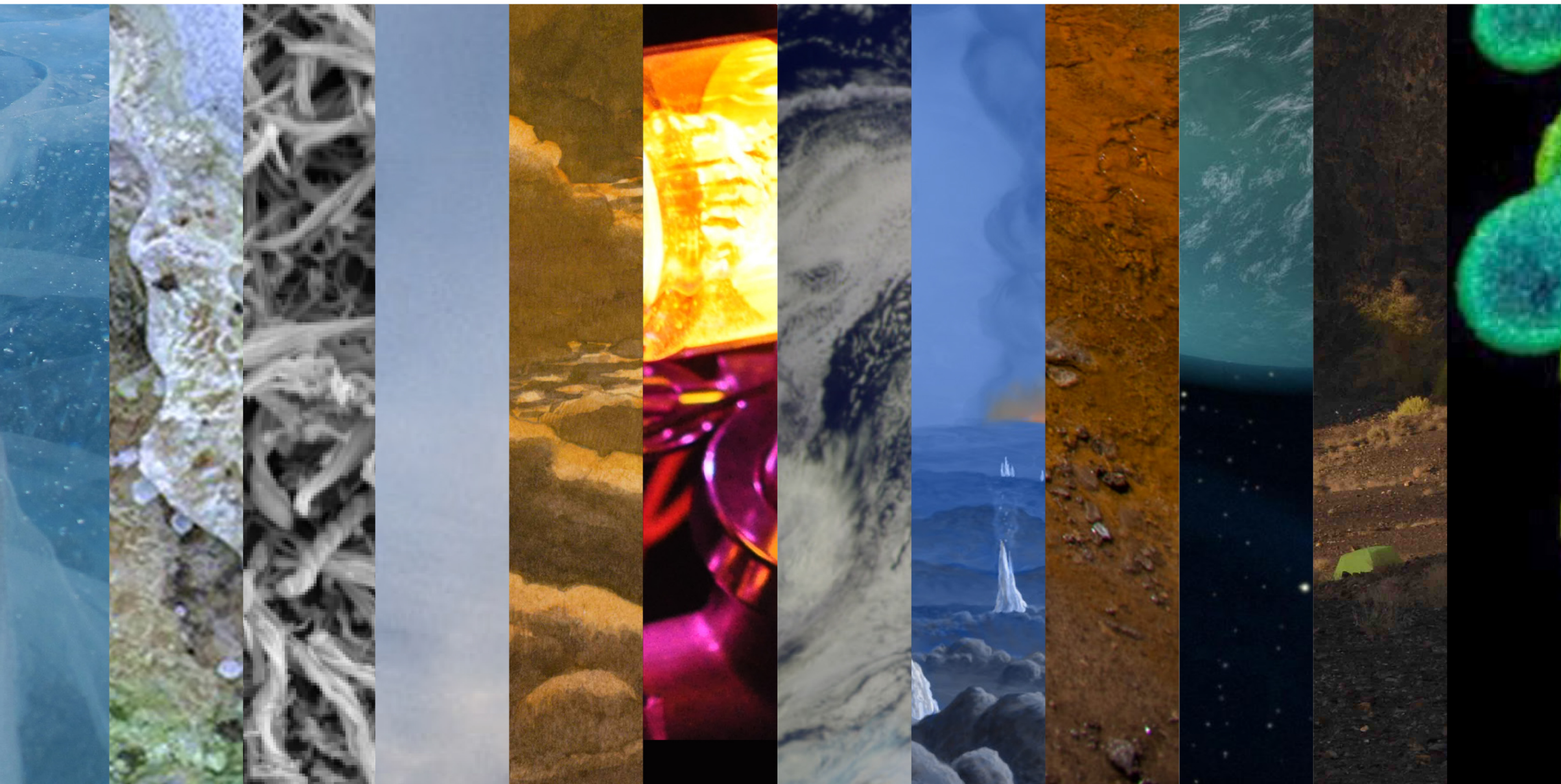


NASA Astrobiology Institute

2017 Annual Science Report

The Virtual Planetary Laboratory

University of Washington, Seattle



The Virtual Planetary Laboratory

Lead Institution:
University of Washington, Seattle

Principal Investigator:
Victoria Meadows

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

Background Image Credit: NASA/JPL-Caltech

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

2017 Executive Summary

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. To enhance the science return from NASA exoplanet missions, VPL uses interdisciplinary exoplanet models that are informed by Earth and Solar System observations, Earth's geological history, and laboratory and field work.

In Task A, we use Earth and other Solar System data to explore planetary processes, habitability detection, and to validate exoplanet models. As a highlight this year we compared the known atmospheric characteristics of Solar System planets and satellites to exoplanets, to predict whether or not a body is likely to have retained an atmosphere (Zahnle & Catling, 2017).

In Task B we explore the atmosphere, interior and biosphere of the alternative habitable environments provided by the Earth though time. We used models to study hydrocarbon haze formation for early-Earth-like planets orbiting different host stars (Arney et al., 2017), and improved our understanding of how the earth remained habitable throughout its history (Krissansen-Totton & Catling, 2017; Charnay et al., 2017). We continued to explore key biogeochemical cycles for nitrogen, carbon and phosphorus (Stüeken et al., 2017a,b,c) and further constrain the Earth's environment and processes as atmospheric oxygen rose (Zerkle et al., 2017; Kipp et al., 2017).

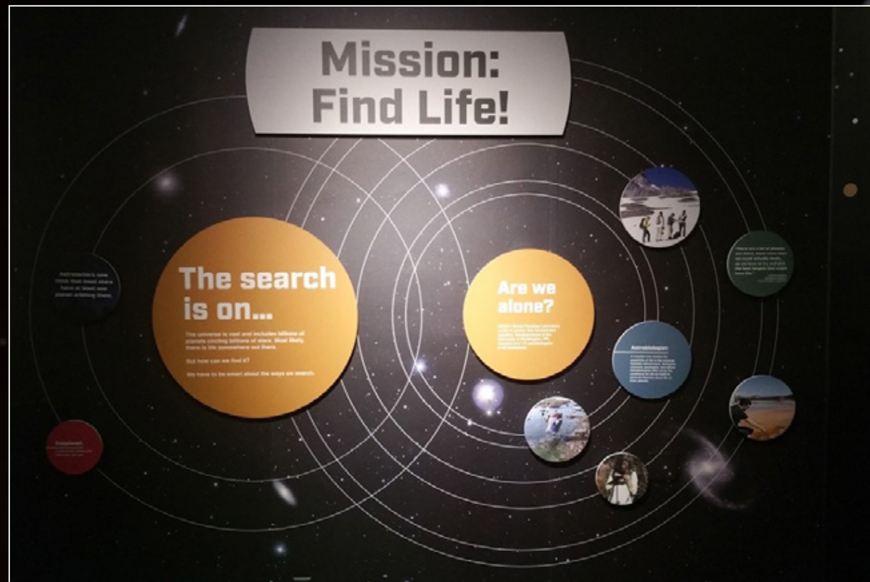
Background Image: This is a 2um near-infrared image of Venus acquired by the Japanese Akatsuki spacecraft from orbit. It shows thermal radiation from the immediately sub-cloud atmosphere escaping up through the clouds. It's just a reminder of how breathtakingly beautiful planets are. Credit: JAXA / ISAS / DARTS / DAMIA BOUIC

In Task C, we study star-planet interactions and their impact on habitability. We published several papers on factors affecting the habitability of exomoons (Hong et al., 2017; Zollinger et al., 2017; Lehmer et al., 2017) and studied periodic orbital and obliquity variations that would impact habitability (Deirtrick et al., 2017). We showed that snowball states are unlikely for synchronous rotators (Checlair et al., 2017), and explored water loss from planets orbiting ultracool M dwarfs like TRAPPIST-1 (Bolmont 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 explored and isolated organisms that carry long-wavelength photosynthetic pigments that might be important for

Fig. 1. (Left) VPL collaborated with several public outreach events this year, included collaborating with the Pacific Science Center to host a special viewing of the 3D IMAX movie "The Search for Life in Space", in December 2018. The special screening included short talks, by VPL scientist Dr. Erika Harnett (pictured), Brett Morris, and Marshall Styczinski, prior to the screening, then a Q&A with the scientists afterwards.Credit: Erika Harnett

Fig. 2. (Right) This year saw the unveiling of the Astrobiology-themed Portal to Current Research space at the Pacific Science Center. The exhibit, titled "Mission: Find Life!", highlighted the key tenants of the search for life in our solar system and beyond, including how activities regarding how extra solar planets are found, why water is considered a key element for the development of life, and what life elsewhere is most likely to look like. The exhibit also featured video interviews from VPL researchers, Dr. Meadows, Dr. Kang, Dr. Parenteau, and Dr. Crisp. The exhibit ran from March 2018 to September 2018. Credit: Erika Harnett



M dwarf photosynthesis (Wolf et al., 2017; Kiang et al, 2017). We also developed the concept of organic haze as a biosignature (Arney et al, 2017b) and developed disequilibrium biosignatures for anoxic environments (Krissansen-Totton et al., 2017b). We also led or contributed to numerous reviews on exoplanet biosignatures.

In Task E we work to improve terrestrial exoplanet detection, target selection, and observing techniques for habitability and biosignature assessment using current and future telescopes. We contributed to the discovery and characterization of the TRAPPIST-1 system (Gillon et al., 2017; Luger et al., 2017b), and performed extensive climate-photochemical modeling of Proxima Centauri b (Meadows et al, in press) and the TRAPPIST-1 planets (Lincowski et al., 2017b,c) to identify environmental states and observational discriminants. We explored new mapping techniques (Fujii et al., 2017b; Lustig-Yaeger et al., 2017), and led or contributed to the development of biosignature detection and interpretation strategy for future observations (Meadows et al., 2017, Catling et al., 2017, Fujii et al, 2017, Walker et al., 2017).

VPL Team members contributed to science or design for several NASA missions, including simulated terrestrial exoplanet observations for JWST; participation in the WFIRST mission, and HabEx/LUVOIR mission concepts; and membership the ExoPAG Executive Council.

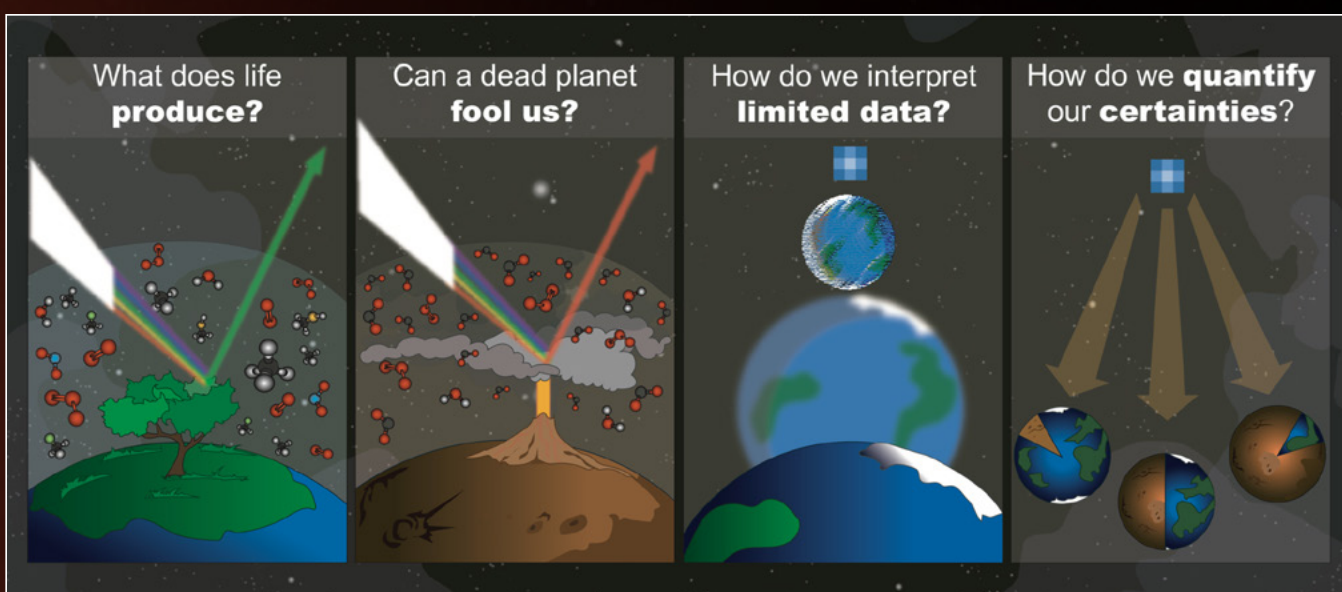


Fig. 3. An overview of the past, present, and future of biosignature theory research. Research historically has focused on cataloging lists of substances or physical features that yield spectral signatures as indicators of potential life on exoplanets. Recent progress has led to understanding of how 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

Background image credit: NASA/JPL-Caltech

Project Reports

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

In this task, we use observations of Solar System planets and moons to explore the detectability of signs of habitability and life in planetary environments, and to constrain planetary processes.

We continued to develop our spectral Earth database by adding a phase dependent dataset (Schwieterman et al., 2017), and developing software to provide phase dependent spectra for Venus and Mars. We used the known atmospheric characteristics of Solar System planets and satellites, and exoplanets, to derive an empirical law based on escape velocity and orbital insolation that can be used to predict whether or not a body is likely to have retained an atmosphere (Zahnle & Catling, 2017). Studying Mars' potentially habitable past, we used a photochemical model to study the reducing power of volcanic gases on ancient Mars (Sholes et al 2017), which may have caused the Martian atmosphere to become anoxic like early Earth. We reviewed the constraints and paradoxes set by climate and volatile budgets of ancient Mars, and their impact on habitability (Haberle et al 2017). Claire contributed to a study considering the Tindouf Basin in Southern Morocco as an analog for Noachian Mars (Oberlin et al 2017), and Parenteau contributed to a summary of the Conference on Biosignature Preservation and Detection in Mars Analog Environments (Hays et al 2017). Zahnle contributed to a study examining the ballistics of impact ejecta on Enceladus (Alvarello et al 2017). In Del Genio et al (2017), we leveraged VPL models to analyze recent trends and advances in Earth weather and climate modeling to guide future modeling of Solar System and exoplanet climates.

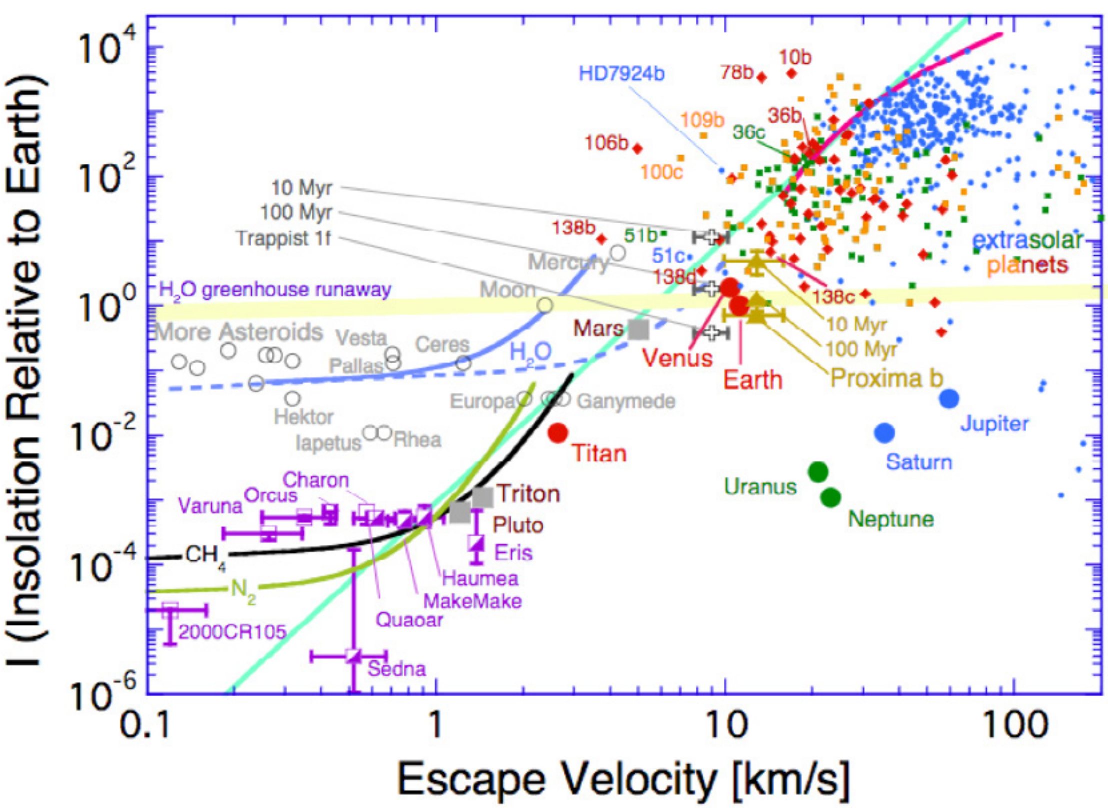


Fig. 4. An empirical description of the relationship between incident radiation, planetary escape velocity, and the presence of a planetary atmosphere. The "cosmic shoreline" dividing planets that have atmospheres from those that don't is given by the aqua line. Atmospheres are found where gravity — here represented by the escape velocity — is high and insolation — here represented by the total stellar insolation at the planet relative to that received by Earth — is low. The presence or absence of an atmosphere on solar system objects is indicated by filled or open symbols, respectively. From Zahnle & Catling (2017).

Task B: Early to Current Earth

We study early Earth to better understand potentially habitable planetary environments that are different to modern Earth and may exist on exoplanets. Claire uncovered high resolution geochemical evidence (Izon et al 2017) that supports the hypothesis of a hazy early Earth, and we examined how organic haze may impact exoplanet spectra (Arney et al 2017a). The sun was fainter in the past, and we modeled temperature-regulating continental and seafloor weathering cycles to better understand how the Earth remained habitable (Krissansen-Totton and Catling 2017; Charnay et al 2017). We used multiple lines of research to understand the Earth's early N cycle including determining the onset of early metabolisms using more reliable N isotope measurements (Stüeken et al, 2017a). Stüeken et al (2017b) also investigated C and N isotopes in Archean lakes, finding that Archean lakes with different environmental conditions supported different metabolisms, with Mesoproterozoic sediments showing that some purported ancient lake settings had seawater input (Stüeken et al, 2017c). We also explored Earth's early phosphorous cycle (Kipp & Stüeken, 2017). Stüeken (2017d) derived a first marine selenium isotope mass balance, increasing sensitivity to complex life. In Koehler et al (2017) we found lower nitrate levels in the Mesoproterozoic compared to preceding and subsequent eons, which would have limited bioavailable nitrogen, and Johnson et al (2017c) adapted a fluorometric technique for measuring NH_4^+ in water to use in geologic samples. Zerkle et al, (2017) showed that the N cycle responded immediately to a more oxic atmosphere when oxygen rose, and Kipp et al (2017) used selenium isotopes to show there was extensive marine suboxia at this time. Johnson et al (2017b) measured N isotopes in glacial tills (0-2.9 Ga), finding evidence of biological N fixation. Johnson et al (2017) found active oxygen production and N cycling during the more recent Marinoan Snowball Earth.

Fig. 5. Professor Roger Buick with 2.65 billion year old Aeolian cross-bedded sandstones that are relics of dunes formed from wind-blown sand near Koegas, South Africa. This year VPL geologists obtained samples from these sites to improve atmospheric pressure determinations for early Earth.

Task C: The Habitable Planet

Research this year included modeling of planet formation, and internal, orbital and atmospheric evolution of terrestrial planets. We examined circumbinary protoplanetary disk evolution (Fleming & Quinn, 2017) and identified observational criteria to distinguish between planet formation scenarios in disks (Szulágyi et al., 2017). We also modeled migrating chains of super-Earths (Izidoro et al., 2017). Exploring the habitability of exomoons, we looked at the impact of planet-planet scattering on exomoons (Hong et al., 2017), and showed that tidal heating will likely sterilize exomoons in the habitable zone (HZ) of low-mass stars (Zollinger et al., 2017), but that water can survive on large exomoons indefinitely when no tidal heating is present (Lehmer et al., 2017). We explored gravitational effects on habitable zone planets, including re-examining tidal locking to show that Earth-Sun analogs may be in danger of synchronous rotation (Barnes, 2017), and the conditions under which exoplanets may undergo Milankovitch Cycle orbital and obliquity variations (Deitrick et al., 2017). Modeling the impact of stellar insolation on planetary climate and habitability, 3D GCMs were used to understand climate for planets near the inner and outer edges of the habitable zone (Abbot et al., 2017; Kopparapu et al., 2017), identify possible climate states for cold and hot start HZ planets (Wolf et al., 2017) and show that snowball states are unlikely for synchronous rotators (Checlair et al., 2017), and that planets with high obliquities can maintain stable equatorial ice belts (Rose et al. 2017). Bolmont et al., (2017) modeled water loss planets orbiting ultracool dwarfs like TRAPPIST-1. Catling and Kasting (2017) published a research-level book surveying atmospheric evolution and climate for planets and exoplanets.

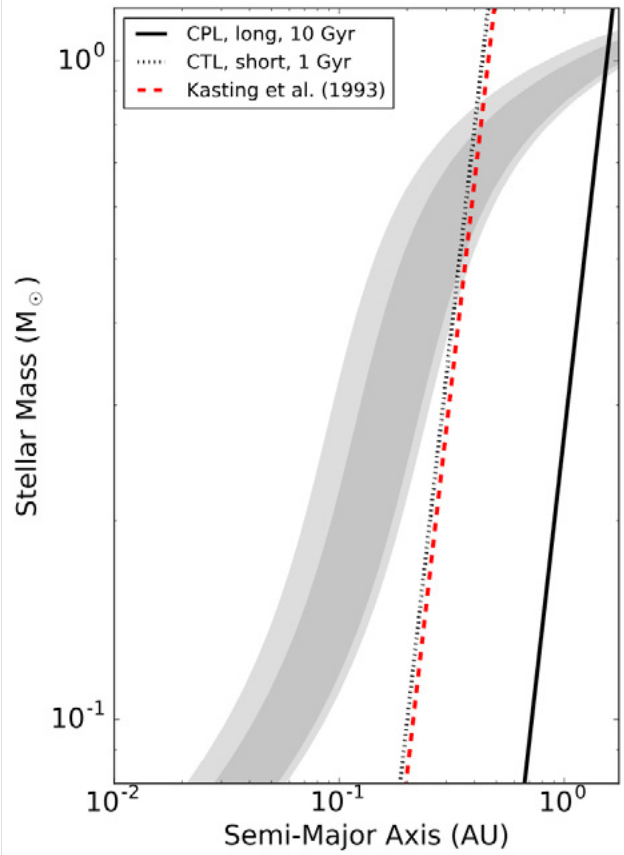


Fig. 6. A re-evaluation of the zone where terrestrial exoplanets are tidally locked, from Barnes (2017). The grey regions are the HZ, and the red dashed curve is the "tidal lock radius" from Kasting et al. (1993). The dotted and solid lines represent limits to tidal locking from different models (constant-phase-lag (CPL) and constant-time-lag (CTL) equilibrium tide models) and different assumptions for age, 1 or 10 Gyr, and initial rotation periods, 8 hr (short) or 10 d (long). Planets with the same tidal properties as the modern Earth may be synchronous rotators in the HZs of GKM dwarfs.

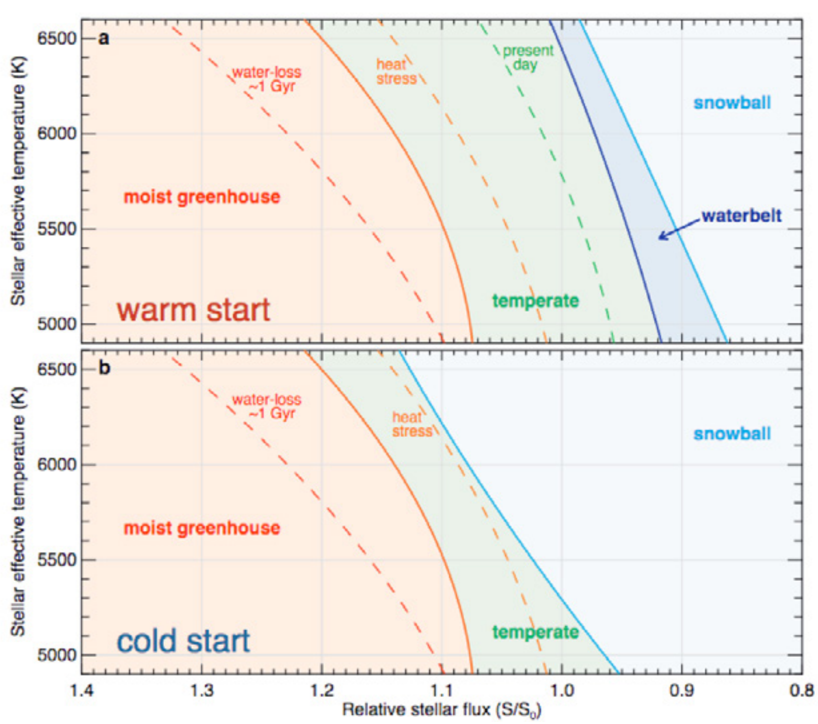


Fig. 7. Circumstellar climate zones as a function of relative stellar flux for Earth-like planets at constant CO2. The top panel assumes an initial state that is warm (i.e. liquid water covers the surface). The bottom panel assumes an initial state of a completely ice-covered planet. Four possible climate states are identified: an uninhabitable moist greenhouse (orange), a habitable temperate climate (green), a habitable "water belt" in which ice lines can reach the tropics (dark blue), and an uninhabitable snowball (ice-covered) state (light blue). From Wolf et al. (2017).

Task D: The Living Planet

Modeling, laboratory, and field work help us understand the co-evolution of the environment and biosphere, identify new biosignatures, and understand their false positives. We considered the history and ecologies of microbial communities, studying the impact of humans on microbial desert oases (Souza et al., 2017), how stoichiometric imbalances change the metabolic capacity of microbial communities (Zarraz et al., 2017), and examining the different evolutionary histories of varied hydrothermal microbial populations (Anderson et al, 2017). To provide insight to how photosynthesis may function around red M dwarf stars, we examined a variety of Chlorophyll d- and f-containing oxygenic phototrophs (Wolf et al 2017), and isolated the original cyanobacterium in which the far-red pigment chlorophyll d was first discovered, finding its peak absorbance wavelength corresponds to the solar radiation peak transmittance by red algae (Kiang et al 2017). Blankenship reviewed the diversity of photosynthetic pigments (Blankenship 2017a), and provided a commentary on new findings on the origin and evolution of cyanobacteria (Blankenship 2017b). We developed novel biosignatures and improved exoplanet biosignature interpretation through environmental context: we examined surface reflectance and polarization biosignatures of anoxygenic phototrophs (Parenteau et al 2017), developed the concept of organic haze as a biosignature (Arney et al., 2017b), developed disequilibrium biosignatures for anoxic environments (Krissansen-Totton et al., 2017b), argued that O2 is a biosignature only in the context of its environment (Meadows, 2017), emphasized the need for "self-skepticism" in biosignature searches (Domagal-Goldman 2017), and explored biosignature future directions (Walker et al., 2017). In significant collaborations with the UCR team, we concluded that the O2-CH4 disequilibrium biosignature pair would have been challenging to detect remotely throughout most of Earth's history (Reinhard et al, 2017a; 2017b), and wrote several reviews on biosignatures in general (Schwieterman et al., 2017b), O2 false positives and negatives (Meadows et al., 2017), Earth's biosignatures through time (Olson et al., 2017), and surface and temporal biosignatures (Schwieterman et al., 2017c).

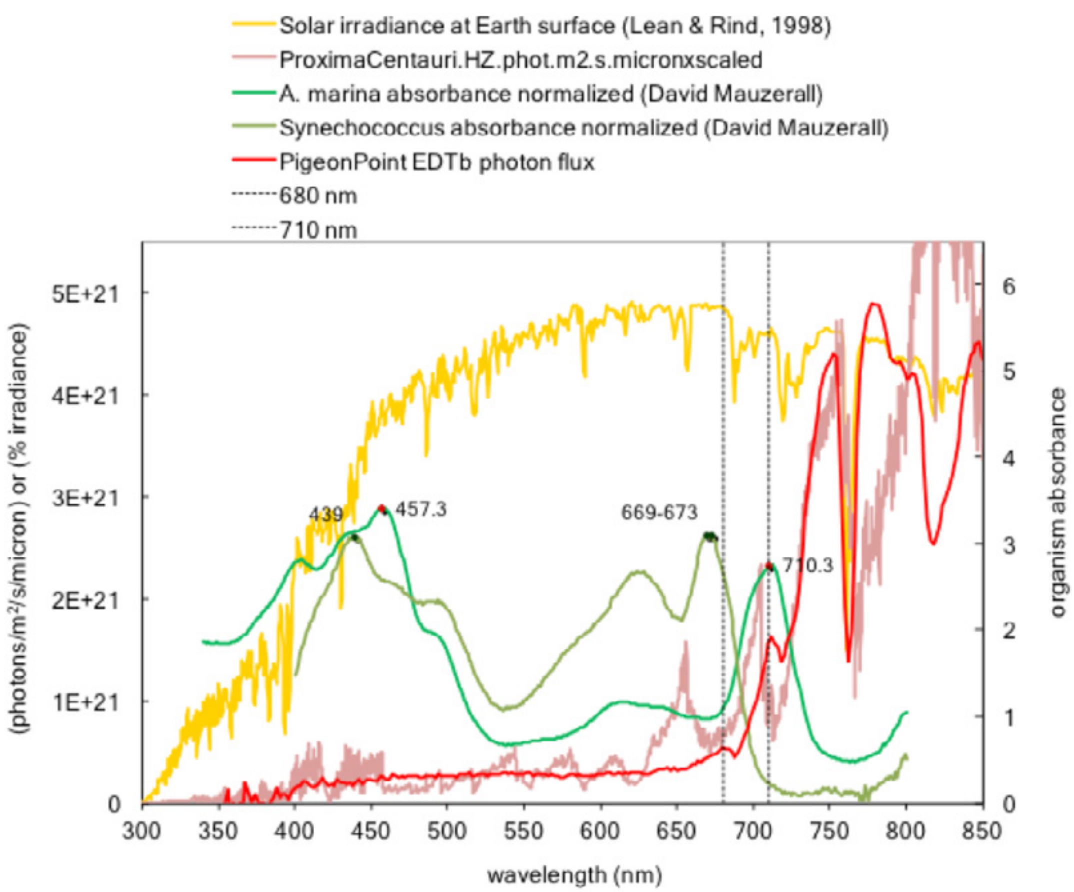


Fig. 8. Comparison of irradiance from the Sun at the Earth's surface (Lean & Rind, 1998), from the red dwarf star Proxima Centauri at a habitable zone distance, and from the Sun transmitted through the algae E. delesseroides (red) showing similarity between M dwarf incident radiation and transmission through red algae. In vivo absorption spectra of Acaryochloris marina MBIC11017 and a Chl a cyanobacterium, Synechococcus are shown for comparison.

Task E: The Observer

In Task E the environments generated in Tasks A-D feed into research to improve terrestrial exoplanet detection, target selection, and observing techniques for habitability and biosignature assessment using current and future telescopes. We contributed to the discovery and characterization of the TRAPPIST-1 system, with seven terrestrial-sized planets (Gillon et al., 2017), and confirming the orbit of TRAPPIST-1h, which revealed the likely migration and potentially volatile-rich composition of the TRAPPIST-1 planets (Luger et al., 2017). We coadded Kepler data to show that the average albedos of super-Earths are low, perhaps indicating cloud-free conditions (Sheets & Deming 2017), and continued to improve polarimetry for exoplanet characterization by understanding polarization noise sources (Cotton et al., 2017a; 2017b). To support the imminent launch of the James Webb Space Telescope, VPL studied processes that affect exoplanet transit observations, including aerosol forward scattering (Robinson 2017) and stellar flux leaks from neighboring spectral regions into the exoplanetary absorption lines (Deming and Sheppard, 2017). We also led extensive climate-photochemical

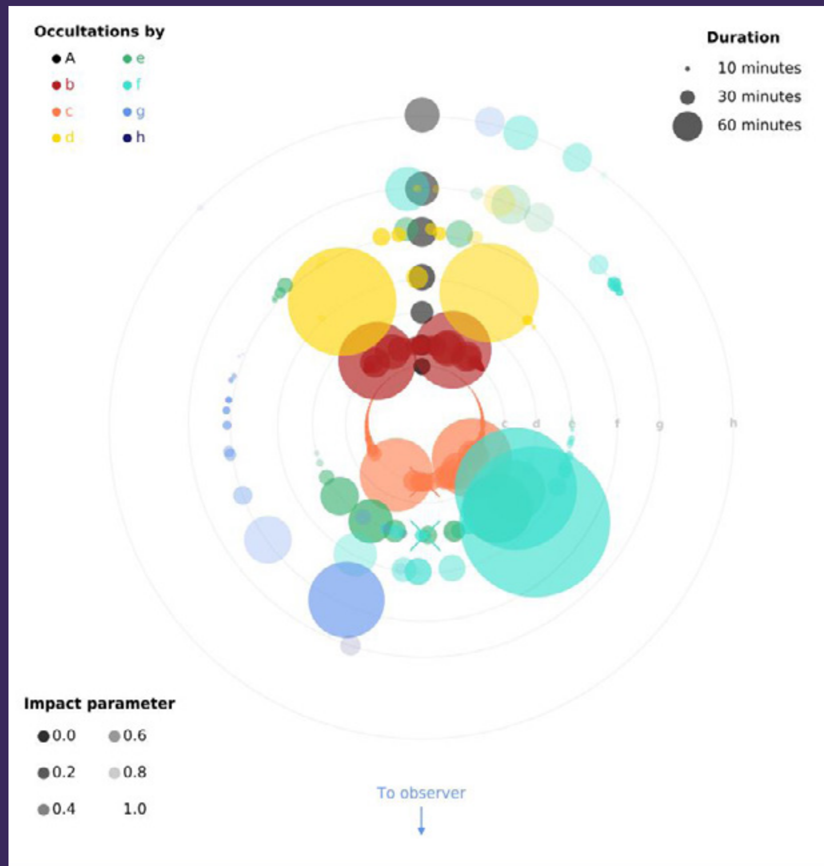


Fig. 9. A top down view of the TRAPPIST-1 exoplanetary system showing the location, duration, and detectability of planet-planet occultations. Planet-planet occultations occur when one planet passes in front of another planet and blocks some of the more distant planet's light. Each colored dot shows one planet-planet occultation over the course of three years, with the planet that is blocked denoted by the light grey circle showing that planet's orbit around the star, the planet that passes in front is identified by the color of the dot, and the relative ease of observing each event is described by the transparency and size of the dot. These type of exoplanetary alignments are frequent between the seven planets in the TRAPPIST-1 system because the planets all orbit very close to the star. Credit: Jacob Lustig-Yaeger

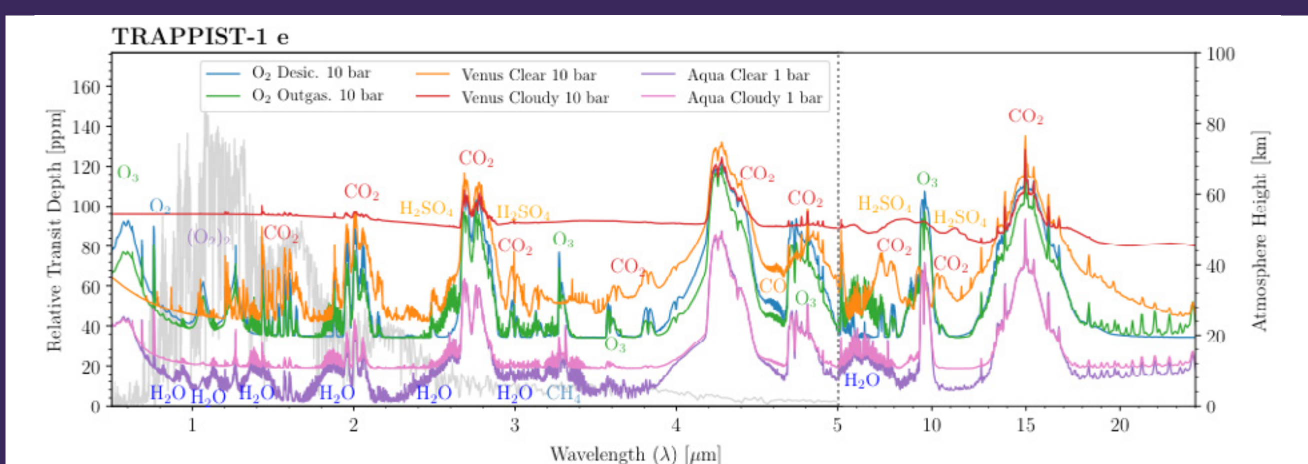


Fig. 10. Simulated transit transmission spectra of a variety of environments modeled for the habitable zone planet, TRAPPIST-1 e. These environments can be distinguished from each other by their spectral features at different wavelengths, which are characteristic of some of their important bulk and trace gases. These gases may be indicative of a potentially habitable environment (e.g. the ocean-covered "aqua planets"), or may indicate a planet whose environment is unlikely to be hospitable to life as we know it, such as the Venus-like and post-ocean-loss, O_2-dominated environments. Credit: Jacob Lustig-Yaeger

modeling of Proxima Centauri b (Meadows et al, in press) and the TRAPPIST-1 planetary system (Lincowski et al., 2017b,c) to better understand environmental states and observational discriminants for these M dwarf planets in transmission and direct imaging. To better characterize terrestrials in future observations we explored new mapping techniques (Fujii et al., 2017b; Lustig-Yaeger et al., 2017), a new technique to use planet-planet occultations for exoplanet characterization (Luger et al., 2017d), searching for exo-aurorae in high-resolution spectroscopic measurements (Luger et al., 2017a), and a statistical approach to identifying habitable planets (Bean et al., 2017). We also led or contributed to a series of review papers that developed biosignature detection and interpretation strategy for future observations (Meadows et al., 2017, Catling et al., 2017, Fujii et al, 2017, Walker et al., 2017), and contributed to the ExoPAG SAG15 (Apai et al., 2017) and SAG16 reports (Domagal-Goldman et al., 2018; Kiang et al., 2017).

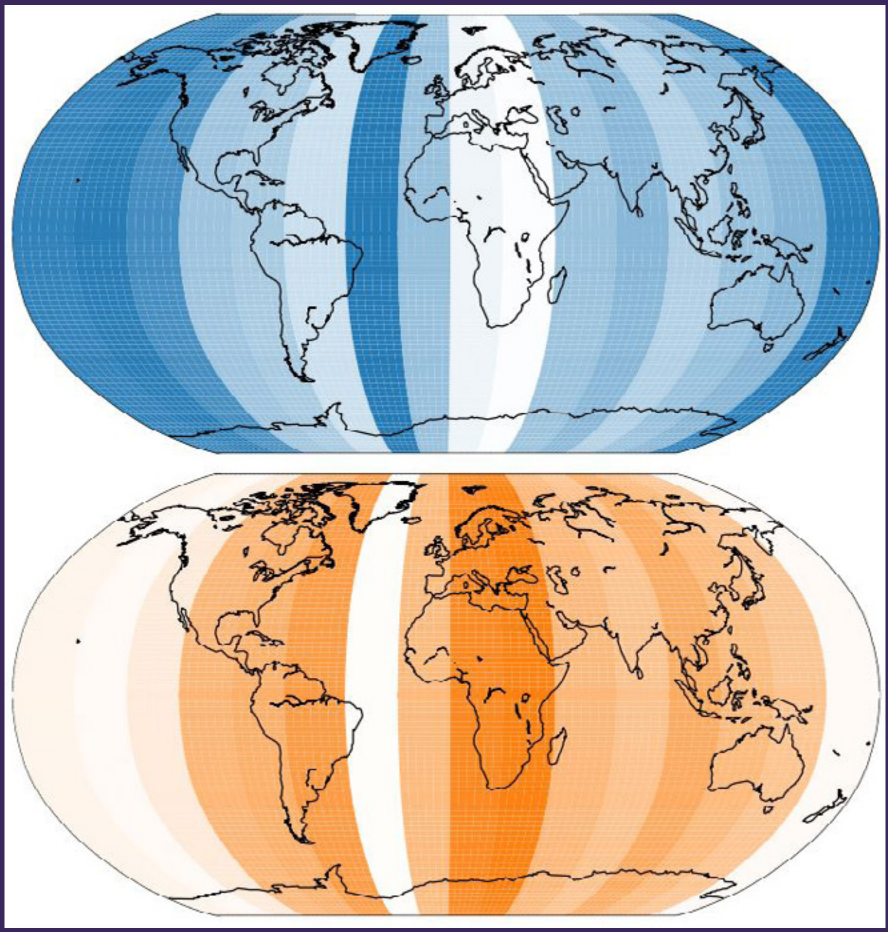


Fig. 11. Maps of the ocean and land of Earth as if it were an exoplanet observed with a next-generation space-based telescope. Even though such a future telescope will not be capable of taking images that can resolve the two-dimensional spatial view of exoplanets, if the planet rotates–as the Earth does once per day–then astronomers can watch as dark blue oceans and light redish-green continents pass in-and-out of view. Computer models can be used to reconstruct crude maps of exoplanets, offering clues into the nature of an exoplanet's geology, oceans, habitability, and presence of life. Credit: Jacob Lustig-Yaeger

Field Work

The VPL Team conducted field work in three locations, Mexico, Wyoming, and South Africa 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.

In August 2017, VPL team members William Sparks, Niki Parenteau, Nancy Kiang, and Kim Bott joined Charles Telesco (University of Florida), Thomas Germer (NIST), Lucas Patty (Vrije Universiteit Amsterdam), Lydia Kreuter (University of Maryland), and William Schap (University of Florida) in a field campaign in Yellowstone National Park to measure the chiral signatures of photosynthetic and chemosynthetic microbial mat communities in the hydrothermal springs. Chirality is a powerful biosignature and, in principle, can be remotely observed on planetary scales using circular polarization spectroscopy. Precision full Stokes spectropolarimetry is required. A new instrument, the Traveling Integrated Polarimetric Spectrograph for Yellowstone (TIPSY), built specifically for this study, incorporated a new concept for spectropolarimetric measurements and has no moving parts and low power consumption, giving it the potential for being a prototype for an instrument for space-flight missions. Sparks is responsible for the instrument concept, while Telesco built the instrument.

The goals of the Yellowstone field campaign were to extend the successful circular polarization measurements of pure cultures of microbes in a controlled laboratory environment to a field remote sensing environment containing complex microbial communities. This work was supported by an NAI Director's Discretionary Fund award.

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 past year a cyanobacterium containing phycobiliproteins with far-red acclimation was isolated from Pozas Rojas, Cuatro Ciénegas, México. It was named Leptolyngbya CCM 4 after phylogenetic analysis and a description of its morphological characteristics. Leptolyngbya was

Fig. 12. VPL team member Kim Bott peers down the telescope of the Traveling Integrated Polarimetric Spectrograph for Yellowstone (TIPSY), built by Charles Telesco, University of Florida (grey shirt) to perform circular polarization measurements of microbes.

Fig. 13. Nancy Kiang (GISS), Kim Bott (VPL, Univ. Washington), Lydia Kreuter (Univ. Maryland), Thomas Germer (NIST), William Sparks (STScI), William Schap (Univ. Florida), Lucas Patty (Vrije Universiteit Amsterdam), and Charles Telesco (Univ. Florida) (not pictured, Niki Parenteau) carrying pieces of the Traveling Integrated Polarimetric Spectrograph for Yellowstone (TIPSY) to perform circular polarization measurements in the Yellowstone backcountry.

Fig. 14. VPL team members William Sparks, Niki Parenteau, Kimberly Bott, and Nancy Kiang collaborate with researchers from the University of Florida (Charles Telesco and William Schap), NIST (Thomas Germer), University of Maryland (Lydia Kreuter), and Vrije Universiteit Amsterdam (Lucas Patty) to develop and field test a spectropolarimeter capable of remotely measuring the chiral signature of biomolecules. This instrument and measurement capability is relevant to life detection on solar system bodies, and potentially exoplanets. This field campaign was supported by an NAI DDF award.

grown in far-red light. Analysis of the hydrophobic pigments extracted from the thylakoid membranes revealed Chl a, d, and f. The ratio of Chl f/a was reversibly changed from 1:12–16 under far-red light to an undetectable concentration of Chl f under white light. Cuatro Ciénegas, a place surrounded by the desert, is a new ecosystem where a cyanobacterium, which grows in far- red light, was discovered. This is very relevant and provides a distinct link to the field work being done at the Montara State Marine Reserve in Moss Beach, California for far red oxygenic photosynthesis. We will actively be working to understand the specific ecosystem parameters of this freshwater isolate and how they correspond to the known marine far red utilizing organisms.

In an attempt to constrain atmospheric pressure on early Earth by measuring the grain size distribution of fossil sand dunes, or aeolianites, Co-I Prof. Roger Buick and student Erik Goosmann traveled to southern Africa to collect aeolianite samples. They visited the ~3.2 Ga Moodies Group, which is reported to contain the world's oldest aeolianites (Simpson et al. 2012), but field observations and thin section analysis of grain-scale features suggest that these rocks were probably not wind-deposited. Instead, in S. Africa the ~2.64 Vryburg Formation was sampled: a probable aeolianite deposited fairly close in time to ~2.7 Ga rocks showing evidence that early Earth had an atmosphere <0.5 bar (Som et al. 2016). Outcrop observations and grain-scale analysis support the aeolian origin of the Vryburg (Goosman et al., in prep.). While on the same trip, they also collected samples of Pongola Supergroup basalt flows eruptedat sea-level in Swaziland and in the Wit-Mfolozi River in South Africa for paleobarometric analysis using the size distribution of gas bubbles (cf. Som et al., 2016). Preliminary analysis suggests that these rocks may not be amenable to this kind of analysis, as the gas bubbles deviate from sphericity and do not have sharp contacts with their host matrix, making X-ray tomography difficult if not impossible.

Team Members

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Giada Arney
Mahmuda Afrin Badhan
Jeremy Bailey
Rory Barnes
John Baross
Cecilia Bitz
Roy Black
Robert Blankenship
Edward Bolton
Kimberly Bott
Amber Britt
Roger Buick
David Catling
Benjamin Charnay
Mark Claire
David Crisp
Russell Deitrick
Drake Deming
Feng Ding
Shawn Domagal-Goldman
Peter Driscoll
Ryan Felton
Y. Katherina Feng
David Fleming
Jonathan Fortney
Colin Goldblatt
Erik Goosmann
Pramod Gupta
Jacob Haqq-Misra
Sonny Harman
Erika Harnett
Suzanne Hawley
Tori Hoehler
James Kasting
Sarah Keller
Nancy Kiang
Michael Kipp
Matthew Koehler
Daniel Koll
Ravi Kopparapu
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Andrew Lincowski
Rodrigo Luger
Jacob Lustig-Yaeger
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Rebecca Payne
Raymond Pierrehumbert
Thomas Quinn
Sean Raymond
Tyler Robinson
Edward Schwieterman
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Holly Sheets
Aomawa Shields
Janet Siefert
Norman Sleep
Sanjoy Som
William Sparks
Eva Stueeken
Matt Tilley
Jon Toner
Guadalupe Tovar
Lucianne Walkowicz
Caitlyn Wilhelm
Yuk Yung
Kevin Zahnle

Virtual Planetary Laboratory: 2017 Publications

Abbot, D. S., Bloch-Johnson, J., Checlair, J., Farahat, N. X., Graham,R. J., Plotkin, D., Popovic, P., and Spaulding-Astudillo, F. (2018). Decrease in hysteresis of planetary climate for planets with long solar days. *Astrophysical Journal* 854 (1). DOI: 10.3847/1538-4357/aaa70f.

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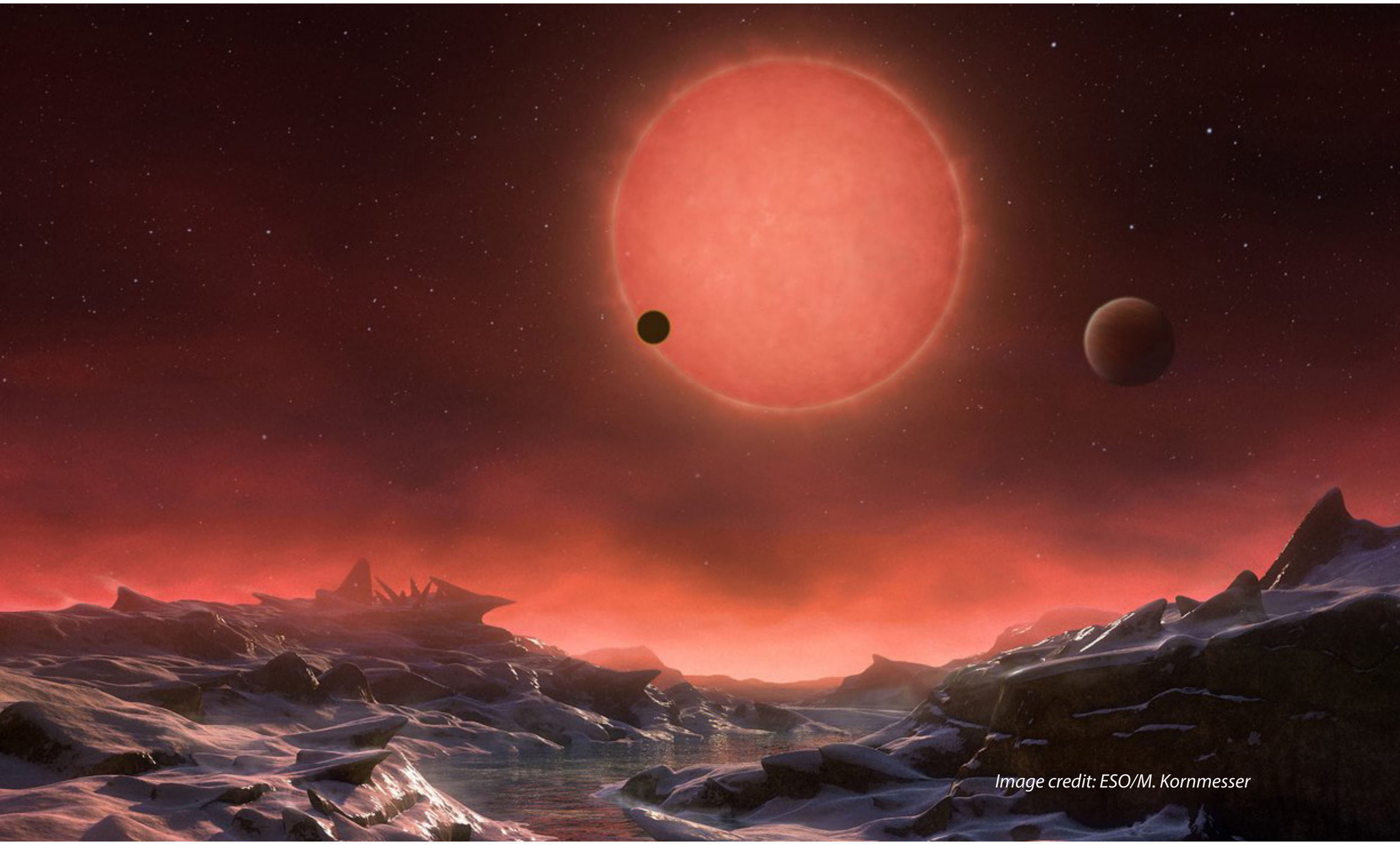
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